Geological history of East Sutherland and Caithness

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Preface

This excursion guide provides the reader with a series of excursions that can be accomplished using Helmsdale, Brora or Golspie as a base in the south of the area and Thurso or Wick in the north. Whilst the aim of the guide is to provide a geological variety to the excursions, it has to be recognised that the main claim to fame of the Jurassic rocks of the area is the spectacular development of the Kimmeridgian Helmsdale Boulder Beds which were deposited on the downthrow side of the Helmsdale Fault during a phase of fault activity. Every year numerous geologists visit the area to examine these rocks, and the rest of the coastal strip of Triassic-Jurassic rocks exposed on the shore and in river valleys. Excursions are also included to cover the other main features of local geology including the Moine basement, the Helmsdale Granite and the Lower Old Red Sandstone (ORS). In Caithness the classic Middle ORS cyclic lacustrine facies, the lake margin unconformities, and the world-famous fossil fish locality at Achanarras Quarry are the main highlights. A selection of other localities has been chosen to illustrate the main features of the ORS of this part of the Orcadian Basin.

The area has been exploited for its geological riches from early times. The Brora Coal was extracted from at least as early 1598 and worked intermittently up to 1974 and the workings abandoned the following year. In early times the coal was used to produce salt by evaporation of sea water, and latterly for domestic consumption and to fire the kilns of the Brora brickworks, which used the Jurassic Brora Brick Clay. The Jurassic sandstones provided the bulk of the local building freestone from quarries at Strathsteven and Clynelish. The discovery of alluvial gold in 1868 at Kildonan resulted in a minor goldrush, and it is still possible to pan small quantities of gold (Excursion 6). With the exploration of the North Sea for hydrocarbons came the discovery of the Beatrice field in 1976, whose production installations can be seen from Helmsdale on a clear day. The field produces oil from sandstones of Middle and Lower Jurassic age which are similar to those of the Brora area.

Several well-known geologists have been associated with the area. Murchison (1827) surveyed the Brora coalfield and Hugh Miller, famous for his work on the fossil fish of the Old Red Sandstone, also studied the area (Miller, 1854, 1859). Judd (1873) provided a detailed account of the Mesozoic succession; his lengthy paper includes much observation of features no longer visible due to poor exposure, modifications to the A9, and filling of quarries. Read *et al.* (1925) described the general geology of the area in the Golspie Memoir of the Geological Survey, to which Lee contributed valuable detail on the Jurassic. The classic contribution on the Helmsdale Boulder Beds by Bailey and Weir (1932) is a masterpiece of careful observation and logical deduction. More recent authors have added detail, but Bailey and Weir's recognition of the effects of submarine faulting contemporary with deposition remains the cornerstone of subsequent work.

This geological history is arranged as far as possible in chronological order, but some events certainly overlap in time. Inevitably the account that follows is the author's personal interpretation, and reference is made to the literature to enable the reader to follow up points of controversy or alternative interpretations.

A general geological map (Figure 1) and a stratigraphic summary (Figure 2) are provided as a reference framework for the reader. Further details of the geological history are included in the introductions to the various excursions. The following account is brief and concentrates on features that are demonstrated by the excursions. More detail, particularly of the tectonic, metamorphic and igneous events, can be found in Trewin (2002) and Macdonald and Fettes (2007).

1. Metamorphic basement

It is not the intention to deal in any detail with the history of the basement in this area for the simple reason that the guide is mainly intended for those interested in the cover sequence. Furthermore, an excellent new guide to Moine geology (Strachan *et al.,* 2009a in press) that updates the previous edition (Allison *et al.,* 1988) includes a geological summary (Strachan *et al.,* 2009b in press), and Excursion 13 in that guide (Strachan *et al.,* 2009c in press) covers the North Sutherland coast in some detail.

From c. 400	Deposition of Lower Old Red Sandstone starting in Emsian, Initiation of Orcadian Basins.Uplift and erosion to expose Helmsdale Granite.
c. 420	Intrusion of Helmsdale Granite.
435–425	Scandian metamorphism deformation and nappe formation, ending with Moine Thrust movements and intrusion of undeformed Strath Halladale granite complex.
c. 470–440	Grampian metamorphic event, peak in mid Ordovician and including migmatites in East Sutherland.Inclusion of basement slices in Moine.
c. 820–870	Knoydartian orogeny seen on west coast of Scotland. Polyphase metamorphism and granite intrusion not proven in E. Sutherland, but some pre-Grampian event probable.
1000–900	Deposition of Moine sediments, mainly sandstones and shales, on metamorphic basement.

The guide can be obtained from the geological societies of Edinburgh and Glasgow. An overall summary of the Moine geology is given by Harris and Johnson (1991) and Strachan *et al.* (2002), and the igneous rocks are covered by Brown (1991). A summary of events affecting the basement is presented in (Figure 3).

In this guide, Moine basement is seen on Excursion 6 in Strath Helmsdale at Kildonan, and beneath the sub-Devonian unconformity at Dirlot (Excursion 5) and at Red Point, Port Skerra and Strathy (Excursion 5). The pre-Devonian basement consists mainly of Moine metasediments, with an inclusion of gneiss (Strathy Complex) which is possibly part of the basement to the Moine (Strachan *et al.,* 2002; Macdonald and Fettes, 2007). These rocks form part of the Naver (=Swordly) Nappe which rests on the Swordly Thrust. This nappe is the highest in a pile of nappes which moved from SE to NW and rest ultimately on the Moine Thrust. Much of the Naver Nappe is highly migmatised and is intruded by the

East Sutherland (=Strath Halladale) migmatitic complex which has been dated at 461 ± 13 and 467 ± 10 Ma on U/Pb ages from zircon rims, showing it to be part of the Ordovician age Grampian tectonothermal event (Kinny *et al.,* 1999).

Basement to the Moine

The oldest rocks in the area form the Strathy Complex which is thought to be a slice of basement gneiss that was brought to its present position along the Swordly Thrust during Grampian age deformation. Inliers of basement in the Moine have been called lewisian', and have provided age dates consistent with the Lewisian. The rocks of the Strathy Complex comprise a variety of gneisses and granulites with trondhjemitic sheets and pegmatites (Strachan *et al.,* 2009c in press). The gneisses include siliceous grey gneiss, quartz-magnetite gneiss, garnet–ortho-amphibole gneiss and hornblende gneiss. In addition, calc-gneisses contain scapolite–diopside–spinel assemblages. Cross-cutting amphibolite dykes and post-orogenic microgranites are also present.

In the gneisses, an early metamorphic assemblage is characterised by garnet, ortho-amphibole and staurolite in a quartz-oligoclase granoblastic matrix. This assemblage is postdated by biotite, sillimanite and blebby quartz.

Moine

The rocks in the area of the guide form part of the Naver (Swordly) Nappe. The sediments were originally pelitic with minor psammite, but psammitic rocks are more frequent in the east. The time of deposition is dated at 1000–900 Ma (Figure 3). The Moine sediments further to the west were deformed by the Knoydartian event around 820–870 Ma, but this event has not been recognised in the area of this guide; evidence may have been largely destroyed by the Grampian event in the Ordovician. The Moine displays an early suite of tholeiitic intrusions now represented by amphibolites, and polyphase deformation has affected these rocks. In the Grampian event upper amphibolite facies metamorphism was associated with two phases of isoclinal folding, and migmatisation took place during the second phase to form the Strath Halladale migmatites. The migmatitic banding was later deformed by tight to isoclinal NW and SE plunging folds, and then intruded by foliated granite and pegmatite sheets. The resulting rocks are characterised by the 'Kirtomy assemblage' of migmatitic pelitic gneisses and granites described in the Moine field guide by Strachan *et al.* (2009c in press).

Scandian deformation resulted in mainly upright, tight SE and NW plunging folds which refolded the previous set. Movement on the Swordly Thrust produced ductile shear zones. Late Scandian events produced monoformal and brittle conjugate folds, with widespread retrogression from the upper amphibolite facies of the peak of metamorphism. Granites intruded at the end of the Scandian event are undeformed and form the Strath Halladale granitic complex. Examples of late granite veins are seen at Portskerra (Excursion 5).

2. Helmsdale Granite

The Helmsdale Granite (Figure 1) is a representative of the Newer Granites in the sense of Brown (1991); it appears to be emplaced along the line of the Helmsdale Fault, which is probably a Caledonian structure. The suite of Newer Granites is calc-alkaline in character and compares chemically with modern magmatic arc products generated by subduction. It is probable that the Helmsdale Granite is related to northward Silurian to early Devonian subduction.

The Helmsdale Granite consists of two phases. An outer zone 1–3 km wide consists of coarse pink, porphyritic adamellite with large pink K-feldspar phenocrysts, and the inner zone is a fine-grained pink-grey adamellite. The two phases appear to have been arranged in a concentric manner and the Helmsdale Fault effectively cuts the intrusion in half. The intrusive contact with the Moine is sharp and steep with little evidence of hornfelsing; presumably the magma was permissively intruded into cold country rocks at a high structural level. The contact between the two intrusive phases is gradational over distances of a few metres to a few hundred metres. Each type of granite has been recorded cutting the other (Tweedie, 1981), and although the fine-grained phase was intruded last, the porphyritic phase was apparently still sufficiently mobile to back-vein the later phase.

Both phases have a similar mineralogy with roughly equal amounts of quartz, plagioclase and K-feldspar. The plagioclase is albite-oligoclase and the K-feldspar mostly orthoclase with some microcline. Both feldspar types are frequently zoned and have zonal sericitic alteration. Biotite makes up to 5% of the rock and accessories include zircon, apatite, magnetite and altered titanite (sphene) (Tweedie, 1979).

The granite was deeply weathered to a grus prior to deposition of the Lower Old Red Sandstone (Emsian), and the pink K-feldspar phenocrysts are a common constituent of the overlying Ousdale Arkose; indeed, it can be difficult to tell the arkose from the igneous rock in the field.

The intrusion has been dated at c.420 Ma by the U-Pb method on zircon (Pidgeon and Aftalion, 1978). The overlying sediments are dated at about 400–390 Ma (Emsian), and thus there was an interval of some 20–30 Ma available for uplift, erosion and unroofing of the granite following cooling. The present day erosion surface is probably similar to the Devonian level.

3. Devonian

Introduction

The Devonian strata of northern Scotland were immortalised by Hugh Miller in his work The Old Red Sandstone' (1841). Hugh Miller's Cottage and Miller House at Cromarty, on the Black Isle, are now a museum of the National Trust for Scotland and well worth a visit. Thick deposits of Old Red Sandstone are present in onshore areas bordering the Moray Firth and consist of a great variety of fluvial, lacustrine and subordinate aeolian strata deposited in the SW portion of the Orcadian Basin. This large inland basin extended north through Orkney to Shetland and as far east as western Norway. In practice, this area included a large number of smaller basins, largely formed by movement on bounding fault systems (e.g. Golspie and Badbea Basins of Dec (1992)). These basins, and the highs that separated them, formed part of a large strike-slip system between Greenland and N. America to the west and Europe to the east (Ziegler, 1982). The Orcadian Basin contains deposits of non-marine origin, with only the faintest sniff of a marine influence at one horizon in the Eday Flagstones of Orkney (Marshall *et al.,* 1996). Marine conditions existed in SW England with a shoreline roughly E–W into Europe, but an embayment of the Middle Devonian sea possibly extended north in the position of the present North Sea as far as the Auk and Argyll oilfields some 200 km SE of Aberdeen. Marine environments also occur to the east in the Baltic (particularly Estonia) (Marshall *et al.,* 2007) and there are strong similarities between fossil fish faunas from Estonia and Caithness (Newman and Trewin, 2008). Rivers and lakes in the Orcadian basin may have ultimately drained to the sea in times of overflow (Trewin, 1986). Areas of compression and areas of extension were created at different times within the Orcadian Basin. There is evidence of extensional tectonics controlling sediment deposition, as well as unconformities which record periods of intra-Devonian faulting, uplift and erosion.

Some authors (Norton *et al.,* 1987, Coward and Enfield, 1987) consider that Devonian sedimentation in the Orcadian area was controlled by 'extensional collapse' of Caledonian crust and that sedimentation took place in half-grabens. The unconformities recognised are then ascribed to footwall uplift and erosion in a generally extensional regime. Those who consider Devonian strike-slip to have been important prefer to interpret the evidence for extension in terms of the presence of transtensional basins, with sediment derived by erosion of transpressional highs (Trewin, 1989). The fact that erosional events appear to be roughly synchronous over wide areas may indicate that there were specific compressive periods associated with strike-slip between Greenland and N. America, but that extensional collapse was superimposed on this system. Work by Underhill and Brodie (1993) using seismic data from the Easter Ross area identifies a period of Lower Devonian extensional faulting which was probably related to rifting, followed by a period of Middle to Upper Devonian regional subsidence.

In northern Scotland the Devonian succession (Figure 4) is divided into Lower, Middle and Upper Old Red Sandstone (ORS). These divisions approximate to Lower, Middle and Upper Devonian time. The stratigraphic nomenclature is complex, with a plethora of names used in different parts of the basin. It is apparent from recent work on the fish faunas that stratigraphic revision is required, and the British Geological Survey (BGS) (2005) have published revised nomenclature for the area near Dounreay (Figure 5) firmly based on fish faunas. The reader is warned that the stratigraphic terminology is currently confusing, since differing schemes and names appear on BGS maps of the area depending on date of publication. The large thicknesses of the Flagstone Groups noted in (Figure 4) are probably excessive due to measurement of total aggregate thicknesses, and lack of appreciation of lateral facies variation. Geophysical gravity data indicates that the ORS succession at any one place in Caithness seldom exceeds 2.5 km. Current work by BGS, incorporating new faunal evidence will lead to better definition of the stratigraphy of the Flagstone Groups in Caithness, and revision of geological maps.

Near the basin margins the three units of the ORS (Figure 1) are separated by unconformities, as present in the Ousdale area (Excursion 4), representing lengthy periods of uplift and erosion. Away from the margin there is apparent conformity between Lower and Middle ORS, as at Sarclet, but a major change in clast derivation is seen. Conformity may also exist between Middle and Upper ORS (Rogers *et al.* (1989)), but all contacts are faulted in Caithness. However, a clear unconformity exists on Hoy, Orkney.

Lower Old Red Sandstone

The Lower ORS in the Helmsdale area is quite variable in character and thickness, and was deposited on the irregular eroded topography of the post-Caledonian land surface. A long period of erosion took place prior to Lower ORS deposition, since the Lower ORS at Ousdale, which is dated on spores as early Emsian (c.390 Ma) (Collins and Donovan, 1977), rests on eroded Helmsdale Granite which is dated at c.420 Ma (Pidgeon and Aftalion, 1978). It is probable that at least 3 km of rock cover was eroded over this period to unroof the Helmsdale Granite, and Moine metamorphic rocks.

The basal deposits of the Lower ORS generally closely reflect the underlying basement geology from which the clasts were derived. Thus, at Ousdale an arkose (Ousdale Arkose, Excursion 4) is present, consisting almost entirely of material derived by weathering of the Helmsdale Granite. To the north at Sarclet metamorphic clasts are much in evidence in conglomerates, although the unconformity is not seen. To the south in the Golspie Basin (Brora outlier), arkosic conglomerate dominates where Helmsdale Granite underlies the ORS, and metamorphic clasts in areas underlain by Moine (Read *et al.,* 1925). The conglomerates of the Golspie Basin were deposited on alluvial fans dominated by debris-flow processes (Dec, 1992).

Deep weathering in Devonian times resulted in granular disintegration of the Helmsdale Granite and the unconformity between arkose and granite is not always clearly defined (Excursion 4). The basal conglomerate and arkose are of variable thickness (up to 200 m) and were deposited on the irregular land surface by alluvial fans and streams, and also by flash floods which followed periodic storms in an otherwise semi-arid climate. Above the coarse basal deposits red mudstones with brown-red sandstones are present. The Ousdale Mudstones are typical of this part of the succession and formed in an alluvial plain environment which was crossed by river channels. Streams were probably ephemeral and flash floods occasionally spread coarse material over the dried mud surfaces. Some permanent water must have been present since a fauna of arthropods left evidence of their activity in the form of trace fossils, and plant debris is present in some of the channel sandstones.

Middle Old Red Sandstone

In the Brora area and north of Helmsdale at Badbea (Excursion 5) the Middle ORS basal conglomerate rests unconformably on Lower ORS and also oversteps Lower ORS to rest on basement (Mykura 1991). Further north at Sarclet the Ellens Goe Conglomerate at the base of the Middle ORS rests with apparent conformity on Lower ORS, but exposures are limited in that area. In general, it appears that a strong phase of folding, faulting, uplift and erosion affected the Moray Firth area, as similar unconformable relationships are seen in many localities to the south of the Moray Firth (Trewin and Thirlwall, 2002), for example at Pennan and Gamrie (Trewin, 1987; Trewin and Kneller, 1987). However, Rogers *et al.* (1989) consider that unconformities, when present, are only of local significance and represent the result of rejuvenation of extensional faults.

To the south of Berriedale the Middle ORS consists mainly of sandstones of broadly fluvial origin, and conglomerates deposited by alluvial fans, the major exception being the lacustrine interlude represented by a thin sequence of laminated siltstones with fish-bearing calcareous concretions, which fired the enthusiasm of Hugh Miller in the last century. These nodule beds at Gamrie, Tynet Burn, Edderton, Eathie and Cromarty (Figure 6) contain the Achanarras fauna of fish and form an extensive marker horizon of Eifelian age in the Orcadian Basin.

To the north of Berriedale the thick (up to 3.9 km aggregate thickness) Caithness Flagstone Groups are found. These rocks are predominantly grey or green in colour, usually dolomitic, and form a series of cyclic deposits recording deposition in a lake of fluctuating depth and extent (Donovan, 1980).

During deep lake periods the dark organic-rich laminated siltstones of the fish beds were deposited in anoxic conditions. The fish carcasses drifted out into the lake and sank in deep water to be preserved due to a lack of scavengers, and the presence of favourable chemical conditions (Trewin, 1986). Most of the fish probably lived in the shallower areas of the lake, where conditions were not suitable for their fossilisation.

As the lake became shallower, more coarsely laminated silts and fine sands were deposited. Lenticular subaqueous shrinkage cracks (Donovan and Foster, 1972) are common, and probably reflect changing salinity in the lake, as is demonstrated by the isotopic ratios of carbon and oxygen, and carbon/sulphur ratios (Hamilton and Trewin, 1988; Duncan and Hamilton, 1988). In the shallow lake phases, fine-grained sandstones with ripple lamination are common, and drying out of the lake is marked by horizons of polygonal desiccation cracks. Evidence of evaporitic conditions is provided by pseudomorphs after anhydrite and halite, and in the North Sea (Well 9/16–3) an anhydrite layer has been recorded representing local hypersaline conditions (Duncan and Buxton, 1995).

The repeated cycles of the Caithness Flagstone Groups are thought to have been climatically controlled. The cycles represent changes from cooler/wetter to warmer/dryer climatic conditions that caused the Orcadian lake to expand and contract (Hamilton and Trewin, 1988). There is agreement that the cycles record Milankovitch periodicities caused by regular changes in the inclinations of the axis of rotation of the earth and in its orbit. The cycles have been assigned to c.20,000 years (Precession) c.40,000 years (Obliquity) and c.100,000 years (Eccentricity) periodicities by various authors (Hamilton and Trewin, 1988; Astin, 1990; Kelly, 1992; Marshall *et al.,* 1996), but authors have not agreed on the duration of the cycles. The problem arises with the choice of depositional rate, and application of the Devonian timescale to the Middle ORS of the area to give an accurate duration for any part of the succession. Recently Andrews (2008) has reviewed all the factors on the basis of the most recent data and concludes that Precession exerted the main control, modulated by Eccentricity. Calculated Devonian values for Precession cycles are 16.7 and 19.7 Ka.

The Achanarras fish bed (Excursion 5) marks a particularly extensive and deep lake phase, and lies at the base of the thickest cycle in the sequence. The fish-bearing part of the sequence was probably deposited over a period of more than 4,000 years, and it contains a remarkable record of changing fish faunas in the Orcadian lake.

Fifteen genera of fish are present at Achanarras including *Dipterus, Coccosteus, Pterichthyodes, Palaeospondylus* and *Mesacanthus* as common representatives, and rarer *Glyptolepis, Osteolepis, Diplacanthus, Cheiracanthus, Rhamphodopsis, Homosteus* and *Cheirolepis.* Further details of the fauna are given in Trewin (1986), and in Excursion 5. A full variety of omnivores (*Dipterus*), scavengers (*Pterichthyodes*) and predators (*Coccosteus* and *Glyptolepis*) are present, representing a food chain with ultimate reliance on phytoplankton. Many of the fish are exceptionally well preserved, and probably died during mass-mortality events.

At the greatest extent of the lake during deposition of the Achanarras fish bed it is probable that the lake overflowed via rivers to the sea to the SE (Figure 6). It is thought that the fish originally migrated into the inland lake system from the sea (Trewin, 1986), since relatives of most of the fish also occur in marine environments, and in other, widely separated Devonian continental areas.

Whilst lake sediments dominate the thick basin-centre sequences, the basin margin deposits include deposits of fluvial floodplains, lake shoreline sands and small aeolian dunes (e.g. Sandside Bay, Excursion 5). In places, rocky shorelines against Moine basement existed (e.g. Dirlot Castle, and Red Point, Excursion 5). The general lake margin environments are illustrated in (Figure 7).

By the end of the Middle Devonian a thick pile of cyclic lacustrine sediments had accumulated in central Caithness with the basal ORS buried to depths of 3 km or more. At the basin margins less subsidence had taken place. Organic matter in fish beds in the deeply buried section would have been generating oil, the relics of which now occur as bituminous residues in fish beds and sandstones. Details of the organic geochemistry are given by Duncan and Hamilton (1988).

Upper Old Red Sandstone

The Upper Old Red Sandstone of Hoy in Orkney has a lava at the base and rests unconformably on Middle ORS flagstones. Wilson *et al* (1935) and Mykura (1976) considered the flagstones below the unconformity to be Upper Stromness Flagstones, but they are now thought to belong to the Rousay Flagstone Formation. The North Scapa Fault cuts the Middle ORS, but became inactive prior to Upper ORS deposition (Wilson *et al.,* 1935). It certainly appears that the majority of the Givetian is not represented. In Caithness the Upper ORS Dunnet Head Sandstone is faulted against Middle ORS. Unconformity is present to the south of the Moray Firth in the Elgin area, and further south in the Midland Valley Middle ORS is entirely absent and Upper ORS rests on folded and faulted Lower ORS. A major period of faulting, folding and uplift of some basin areas clearly took place in Scotland during a phase of compression towards the end of Middle Devonian times. In Shetland, the Walls and Sandness formations were subjected to intense folding and granitic intrusion at about this time (c.360–370 Ma) (Mykura, 1991). Thus, there is evidence of a major compressive episode in the evolution of the major strike-slip belt at this time.

In contrast, Rogers *et al.* (1989) contend that there is much room for doubt with regard to the traditional stratigraphy. On the basis of palynological evidence they discount the presence, in several areas, of an unconformity between Middle and Upper ORS. They regard extensional tectonics as the controlling mechanism for sedimentation, and have no need for periods of transpression. However, exposure is poor in the area, so making interpretation of the outcrop data ambiguous; a transpressive phase producing a gap in the section representing say two million years would be difficult to detect by palynology. Underhill and Brodie (1993) have interpreted seismic data from Easter Ross and favour early Devonian rifting followed by Middle to Late Devonian subsidence. There does not appear to be a marked break between Middle and Upper ORS in their seismic interpretation of this part of the basin. It is possible that in some basinal areas subsidence continued from Middle to Upper ORS, whilst transpressive uplift and erosion was more effective in basin marginal areas.

The Upper ORS consists dominantly of red–yellow sandstones of fluvial origin, and only rarely are fish remains found, apart from the well-documented faunal sequence of the Elgin–Nairn area summarised by Mykura (1991). The affinities of the fish faunas with Baltic forms reflects greater connection between river systems of northern Europe at this time, and a new basin configuration is inferred. The Upper ORS is present offshore in the Buchan Field where it passes conformably upwards into Lower Carboniferous rocks consisting of sandstones and shales of alluvial or deltaic aspect, which contain terrestrial plant debris. The fact that derived Carboniferous spores are found in Lias strata at Golspie (Windle, 1979) attests to the probable presence of Carboniferous in the Inner Moray Firth. Carboniferous strata have been described from the Outer Moray Firth by Leeder *et al.* (1990).

4. Post-Caledonian igneous activity Devonian

Lavas and volcaniclastic rocks occur within the Middle ORS of Orkney and at the base of the Upper ORS, but no examples occur within the area of this guide.

Permo-Carboniferous

Within the area of the guide, there are a few examples of igneous activity which are generally assigned to the Permo-Carboniferous. Monchiquite dykes with a general ENE–WSW trend occur in the Dunnet Head region (see (Figure 1)) and are roughly parallel to the trend of similar monchiquite and camptonite dykes in Orkney.

Two small vents are also present at Burn of Sinnigoe, Dunnet Head (Excursion 5, Locality 15) and at Duncansby (Excursion 5, Locality 7). They are filled with basalts, agglomerates and sedimentary clasts. The igneous rocks in the neck at Duncansby were described as nepheline basalts by Crampton and Carruthers (1914) and this vent has been dated as Permian (255 Ma by K/Ar method on basaltic material; see legend of BGS Sheet 116E, Wick). Although most clasts in the vents are of Old Red Sandstone lithologies, some clasts of basement gneiss have also been recorded.

Tertiary

No examples of Tertiary igneous activity are known in the area of this guide, but tuffs from volcanoes on the west coast contributed to Tertiary sediments in the North Sea, particularly in Palaeocene times.

5. The Inner Moray Firth Basin

The coastline from Inverness to Wick is strongly controlled by the Great Glen and Helmsdale faults which have played a major role in the development of the Inner Moray Firth Basin (Figure 8). The presence of a dominantly Mesozoic basin had long been apparent from the marginal Mesozoic onshore outcrops, and presence of Mesozoic erratics transported onshore by ice during the Pleistocene glaciations. Work by the Geological Survey (summarised by Chesher and Lawson, 1983) identified the major structural elements, but most research was connected with the search for oil and gas, particularly following the discovery of the Beatrice Oilfield in 1976.

The Inner Moray Firth Basin is coincident with part of the Devonian Orcadian Basin and it is probable that the same basement faults influenced both basins. Following Devonian deposition, which probably continued into the Lower Carboniferous, a period of faulting, uplift and erosion occurred. Intense shearing affecting Devonian arkose and Helmsdale Granite along the Helmsdale Fault (Excursion 3, Itinerary 4) is pre-Mesozoic in age and might relate to strike-slip displacement in Carboniferous times (Flinn, 1992). On the basis of seismic interpretation of the Easter Ross area Underhill and Brodie (1993) also recognise an event of compression and inversion in the Permo-Carboniferous.

Deposition resumed in Permian times with basin-marginal aeolian dune sandstones preserved at Hopeman to the south of the Moray Firth and offshore evidence of Permian evaporites in the basin centre (Taylor, 1990; Glennie, 2002). Triassic sediments are extensive in the Inner Moray Firth, and although Frostick *et al.* (1988) proposed that the Great Glen Fault acted as a rift-margin fault controlling sedimentation, their view was not supported by evidence from the offshore area showing that the Great Glen Fault had no influence on thickness of the Permian to Jurassic section (Underhill, 1991).

The Wick and Banff fault systems define the north and south basin margins (Figure 8) between which McQuillan *et al.* (1982) considered some 5 to 6 km of extension took place in Triassic to Cretaceous times, and was accommodated by dextral movement of the Great Glen and Helmsdale faults. Roberts *et al.* (1990) suggested that some 2 km of displacement may have formed a small Permian half-graben in the centre of the basin and that the later c.6 km of displacement took place in the late Jurassic. Roberts *et al.* (1990) interpreted structure seen on seismic sections across the Great Glen Fault as indicative of strike-slip movement, but Underhill (1991) has convincingly demonstrated that the Great Glen Fault was effectively pinned during Mesozoic extension, and certainly had no effect on Jurassic deposition. Thomson and Underhill (1993) consider that rifting took place during the Permo-Triassic and again in the late Jurassic. The Helmsdale Fault was probably the main feature controlling sedimentation during both periods and formed the effective basin margin. In the Lower Cretaceous a shift in depocentres (Andrews *et at,* 1990) reflects a change in the stress regime with different faults controlling deposition.

Underhill (1991) recognised that structures affecting Mesozoic rocks along the line of the Great Glen Fault are of Tertiary origin, and Thomson and Underhill (1993) related such tectonism to the geographical position of the Moray Firth between Atlantic rifting and Alpine fold-thrust tectonic regimes. Local transpression in the Tertiary resulted in the fold structures seen in the Upper Jurassic north of Helmsdale (Excursion3, Itinerary 4.), which Thomson and Underhill (1993) relate to the interaction of sinistral strike-slip on the Helmsdale Fault and dextral movement on the Great Glen Fault. Further discussion of basin development is given in the following stratigraphic sections.

6. Permo-Trias

Deposits of the New Red Sandstone have a sporadic distribution onshore in northern Scotland, but are extensively represented offshore with thick sequences in the Minch and Hebrides basins against the Minch Fault, in the West Shetland Basin, and extensively within the Inner Moray Firth and the North Sea (Glennie, 2002).

Onshore deposits in the Moray Firth area are restricted to the Permian and Triassic of the Elgin area to the south of the Firth, and a small area of Triassic outcrop at Golspie (Excursion 1) in the area of this guide (Figure 9). The present shoreline of the Moray Firth approximates to the margin of the Triassic and earlier Permian basin area, and coincides broadly with the earlier Devonian basin. Northern Scotland lay about 15° north of the equator in Permian times, increasing to more than 30° by late Triassic. The climate was semi-arid to arid and deposition was dominated by flood deposits of fluvial systems near the land areas (e.g. Burghead Beds), together with aeolian sandstones (e.g. Hopeman Sandstone, Lossiemouth Sandstone). Basin centres received the finer detritus of sand and mud with resulting fine sandstones and mudstones deposited on widespread alluvial plains and in playa-lakes.

The dominantly aeolian Hopeman Sandstone (Glennie, 2002) forms the lower part of the Permo-Triassic succession to the south of the Firth, and the discovery of a *Dicynodon* skull (Clark, 1999) dates this sandstone to the Late Permian. Coastal outcrops of the Hopeman Sandstone consist of upper and lower dune-bedded units separated by a unit of distorted and disrupted dune bedding with evidence of reworking by water. Glennie and Buller (1983) have suggested that these disruption structures were formed during the Zechstein (Upper Permian) marine transgression. Marine Zechstein occurs offshore in the Moray Firth (e.g. wells 12/23–1 12/30–1; Taylor, 1990) and a dune belt could have bordered this arm of the Zechstein sea.

The rest of the Permo-Triassic succession of the Elgin area comprises the dominantly aeolian Lossiemouth Sandstone, which has yielded Upper Triassic reptiles (Benton and Walker, 1985), and the fluvial Burghead Beds. These Triassic sandstones and pebbly sandstones are about 150 m thick in the Elgin area, but thicken to 500 m, and are much finer-grained in the offshore area, containing siltstones, mudstones, thin limestone and evaporite beds (Frostick *et al.,* 1988). Deposition in the basin centre may have taken place in ephemeral lakes.

To the south of the Moray Firth the top of the Trias is marked by the Stotfield Cherry Rock. This rock is believed to be a fossil soil profile formed in semi-arid conditions and is probably an altered calcrete rather than a silcrete (Frostick *et al.,* 1988). The horizon is widespread in the Inner Moray Firth and is present as a calcrete at Golspie, where it overlies Triassic mudstones and sandstones (Excursion 1). The Triassic sandstones at Golspie are mainly waterlain but contain abundant well-rounded quartz grains formed by aeolian transport, and some cross-bedding is of probable aeolian origin. These rocks are similar to the Lossiemouth Sandstone to the south of the Moray Firth. The fact that the calcrete forms an extensive seismic marker horizon in the Moray Firth (Linsley *et al.,* 1980; Underhill, 1991) indicates that at the end of the Triassic deposition was slow, the climate semi-arid, and surrounding topography subdued. The Great Glen Fault certainly did not form an active rift margin at this time, and deposition was continuous across the line of the fault.

Thus, at the close of the Triassic, the relatively subdued Grampian and Highland areas bordered an extensive spread of alluvial plain and playa deposits in the Moray Firth. As Europe moved further away from the equator a major climatic change took place to a more temperate climate, and the Triassic basins were invaded by the shallow shelf seas of Jurassic times.

For further information on the Elgin area the reader can consult Glennie (2002) in The Geology of Scotland', the Elgin memoir (Peacock *et al.,* 1968), Glennie and Buller (1983), Frostick *et al.* (1988) and the excursion guide by Gillen (1987).

7. Jurassic introduction

The coastal outcrop of Jurassic rocks from Golspie to north of Helmsdale at Dun Glas is bounded to the NW by the Helmsdale Fault (Figure 1). The local base of Jurassic is generally considered to lie below the Dunrobin Pier Conglomerate, but the contact with the underlying Triassic calcrete is not exposed. It is possible that Rhaetic strata are present, since the marine transgression from the south, and a change to a wetter climate, commenced in the late Triassic. The general succession (Figure 2), which ranges from Lower Jurassic (Hettangian) at Golspie in the south to Upper Jurassic (Volgian) to the north of Helmsdale, is virtually complete apart from a gap in the Lower–Middle Jurassic where Toarcian and Bajocian strata are not represented. The gap could be due to non-exposure or strata cut out by faulting, but in view of the known offshore stratigraphy it is likely to be due to unconformity caused by uplift of the North Sea Dome and associated Jurassic volcanic activity. (Underhill and Partington, 1993; Underhill, 1998). Another possible gap is present in the Upper Oxfordian, but this cannot be tested due to lack of exposure. The Jurassic strata are covered in Excursions 1, 2 and 3 to which the reader is referred for geological detail. The Jurassic history of the area falls into two sections. The first concerns all the Jurassic strata up to the Ardassie Limestone of the Balintore Formation (Mid–Late Oxfordian) which constitute a great variety of lithologies representing environments ranging from alluvial to lagoonal and shallow marine. The second section is the dominantly Kimmeridgian succession of shales, sandstones and boulder beds which were deposited on the downthrow side of the active Helmsdale Fault, and form some of the most spectacular deposits of the British Jurassic. For a general account of the Jurassic of Scotland see Hudson and Trewin (2002).

Whilst the Jurassic of Brora–Helmsdale is the main onshore outcrop area, there are small exposures of parts of the succession against the Great Glen Fault at Eathie (Waterston, 1951; Wignall and Pickering, 1993), near Balintore and Port an Righ (Sykes, 1975a), and to the south of the Moray Firth in the Lossiemouth borehole (Berridge and Ivimey-Cook, 1967). The Inner Moray Firth is a Mesozoic basin area and remains an oil exploration area, although the only major commercial success to date is the Beatrice Oilfield discovered by Mesa Petroleum in 1976 (see Economic Geology). Offshore drilling and seismic surveys have provided much information on the offshore Jurassic, which has been summarised by Glennie (1998). Useful contributions to the understanding of the Moray Firth area have been by Andrews and Brown (1987), Andrews *et al.* (1990), Underhill (1991) and Stephen *et al.* (1993).

Hettangian to Mid-Oxfordian

The Lias stratigraphy of the Golspie area (Figure 9) was revised by Batten *et al.* (1986) who obtained a flora from the Dunrobin Pier Conglomerate (Excursion 1) which had previously been considered unfossiliferous (Neves and Selley, 1975). The stratigraphic nomenclature has been subsequently modified by Richards *et al.* (1993) (see also Excursion 1). This conglomerate contains numerous clasts from the underlying Triassic calcretes and sandstones which had presumably been locally uplifted and eroded, possibly by early movements on the Helmsdale Fault. The conglomerate was deposited in an alluvial fan environment with current transport to the NE; it does not occur in offshore boreholes, and is probably restricted to the basin margin. The flora present is of terrestrial origin and is probably of Hettangian age, but a Rhaetian age is not entirely excluded. This deposit marks a change to a more humid climate with evidence of a rich vegetation cover on the Scottish landmass.

The succeeding strata of the Carbonaceous Siltstone and Clay Unit of the Golspie Formation are very seldom exposed, but from borehole evidence deposition under dominantly freshwater conditions in an alluvial plain environment has been suggested (Neves and Selley, 1975). Within this succession influxes of dinoflagellates indicate minor marine incursions, possibly associated with brief establishment of lagoonal conditions. Similar rocks rest on the Triassic offshore in the Beatrice Oilfield and also occur at Lossiemouth to the south of the Firth.

The White Sandstone Unit (= Mains Formation, (Figure 9)) is a medium- to coarse-grained cross-bedded sandstone which separates dominantly freshwater deposits from overlying marine shales and thin sandstones of the Lady's Walk Shale Member. Deposition of the White Sandstone took place at, or close to, the contemporary coastline; it is interpreted as the deposits of an estuarine channel environment. Land-derived plant debris is abundant together with marine bivalves (Lee, 1925) and marine microplankton (Neves and Selley, 1975).

Above the White Sandstone, the Lady's Walk Shale Member is of shallow marine origin, and records the first Jurassic marine invasion of the Inner Moray Firth in Sinemurian times. The shales range up to Pliensbachian age on the basis of a sparse ammonite fauna. A great variety of lithologies is present, but the sandstones contain the richest marine fauna, which includes bivalves (oysters and pectinids) and rhynchonellid brachiopods. Individual beds have distinctive faunas which were suited to prevailing bottom conditions. In silty shales and mudstones at the top of the exposed section shallow sand-filled scours containing quartz pebbles, wood fragments, and marine bioclastic debris are present, and attest to rapidly changing environments and proximity to land. The numbered bed sequence given by Lee (1925) generally cannot be followed due to poor exposure caused by a cover of beach sand. In a regional context, the marine invasion of the Inner Moray Firth is later than that seen on the west coast of Scotland, where open marine conditions were established in Hettangian times in the Hebrides basins (summary in Hudson and Trewin, 2002).

Toarcian and Bajocian age sediments are not exposed onshore. Offshore the sandstones of the Orrin Formation, although assigned to the Toarcian–Bajocian by Andrews and Brown (1987) are now considered to be of Pliensbachian to

Toarcian age (Stephen *et al.,* 1993). These sandstones show an upward transition from marine shoreface enviroments to those of a beach barrier and interdistributary bay complex (Stephen *et al.,* 1993).

The Bathonian Doll Member of the succeeding Brora Coal Formation ((Figure 10) and Excursion 2) is of fluvial origin with channel sandstones and alluvial plain mudstones (Hurst, 1981). Siderite and abundant kaolinite are present as well as a sparse fauna of freshwater ostracods; the freshwater bivalve *Unio* was recorded from the top of the Member by Neves and Selley (1975). Drifted plants occur in the shales, some of which, including several species of *Equisetum* (mare's-tails) together with *Ginkgo, Goniopteris, Todites* and *Cladophlebis,* formed the subject of Marie Stopes' first palaeobotanical paper (Stopes, 1907). Offshore in the Beatrice Oilfield similar kaolinitic and siderite mudstones with thin sandstones containing rootlet casts are present.

The Inverbrora Member of the Brora Coal Formation is considered to be of lagoonal origin. Lam and Porter (1977) first noted the presence of marine micro-plankton elements (dinoflagellates) and a study by MacLennan and Trewin (1989) showed that marine influence is extensive with high abundance/low diversity dinocyst assemblages present. Shell beds of *Neomiodon* and *Isognomon* together with ostracods were winnowed on the lagoon floor during phases of marine invasion. The sediments are dominated by dark organic-rich shales (up to 27% Total Organic Carbon) which locally approach oil-shale in character and were deposited during stagnant lagoonal phases. Pyrite is abundant, probably reflecting that abundant sulphate was periodically available from sea water.

In the Beatrice Oilfield, this lagoonal facies is absent or very thin, but it is represented to the south of Brora at Cadh' an Righ, with similar lithologies, fauna and palynological character to those of Brora (MacLennan and Trewin, 1989). The lagoonal area (Figure 11) probably extended parallel to the Helmsdale Fault system and was periodically invaded by the sea from the NE in the region of the Wick Fault, with the ocean connection through the Viking Graben. An alternative explanation is that the sea entered the Moray Firth through the Great Glen from the west coast.

The Brora Coal overlies the lagoonal Inverbrora Member. This coal, which has been extensively worked in the Brora area (see Economic Geology Section) is also present in the Beatrice Oilfield and onshore to the south at Cadh' an Righ. The coal generally lacks a seat earth, initial deposition being from drifted plant material. The lagoonal area was cut off from the sea at this time and swamp conditions, probably similar to a floating bog, spread over the lagoon area. The coal contains coniferous wood and masses of *Equisetum* (Harris and Rest, 1966). Palynology preparations of the coal are highly variable, representing local plant communities, and marine microflora is absent (MacLennan and Trewin, 1989).

The Bathonian/Callovian boundary has frequently been positioned above the coal, but from palynological data, probably lies within the Inverbrora Member (MacLennan and Trewin, 1989). Overlying the coal at Brora, at the base of the Brora Argillaceous Formation (Figure 10), is the Brora Roof Bed, a bioturbated shallow marine transgressive sandstone with a Shelly fauna dominated by bivalves. This bed marks the main Callovian marine transgression in the area (Sykes, 1975a). Reworked coal fragments occur in the Roof Bed, and to the south of the area at Cadh' an Righ sand-filled burrows extend down into the coal from the Roof Bed. Rapid deepening of the sea resulted in deposition of the Brora Shale with a diverse marine macrofauna of bivalves together with belemnites and ammonites. The environment was clearly open marine at this stage, but a high proportion of land-derived spores and plant debris attests to the close proximity of the Scottish landmass.

In the Beatrice Oilfield the coal is followed by a few metres of shale in which the transition to open marine conditions takes place. Several (usually four) thin sandstones, generally forming coarsening-up sequences representative of marine bars, appear to be the broad time equivalent of the Roof Bed (the 'B' sandstones of the Beatrice Reservoir, (Figure 12)). The Mid-Shale overlies the 'B' sandstones and compares well with the Brora Shale, with similar faunas and palynofacies characteristics (MacLennan and Trewin, 1989). A general comparison of this part of the Brora section with that of Cadh' an Righ and Beatrice is given in (Figure 12).

Overlying the Brora Shale at Brora is the Glauconitic Sandstone Member, which contains highly glauconitic beds also rich in siderite and phosphatic concretions. Belemnites are particularly abundant and the sandstones are extensively bioturbated. This member represents a period of slow deposition at Brora, but to the south at Cadh' an Righ a nodule bed represents a condensed sequence, or possibly a non-sequence. In Beatrice Oilfield wells, phosphatic concretions present near the base of the 'A sandstone are probably the lateral equivalent of the Glauconitic Sandstone Member.

At Brora the rest of the Brora Argillaceous Formation (Figure 10), together with the Brora Arenaceous Formation, forms a marine coarsening-up sequence commencing with offshore marine clays of the Brora Brick Clay Member and culminating in the cross-bedded porous, pebbly sandstones with moulds of marine bivalves typical of the Brora Sandstone. These sandstones were probably deposited in a coastal marine bar system oriented parallel to the Scottish landmass. A similar coarsening-up marine bar sequence occurs in the Beatrice Oilfield where it forms the main oil reservoir, the 'A' sandstones (Figure 12). However, the coarsening-up sequences of Brora and Beatrice are not synchronous, the top of the Brora sequence being Oxfordian (*plicatilis* Zone) and that at Beatrice Callovian (*lamberti* Zone) (Figure 11). Contrasting subsidence rates and sand supply in the two areas may account for the difference.

This part of the Jurassic sequence at Brora is completed by the transgressive Ardassie Limestone Member (Figure 9) of the Balintore Formation, which consists of shales and muddy limestones with calcitised *Rhaxella* (sponge) spicules. These rocks are intensely bioturbated with *Chondrites, Thalassinoides* and other trace fossils; they also contain thick-shelled oysters (*Gyphaea dilatata*), fan mussels (*Pinna lanceolata*)and belemnites. Ammonites of *plicatilis* Zone were recorded by Sykes (1975a). Offshore in the Beatrice Oilfield the Oxfordian is represented by marine shales, but further offshore the Alness Spiculite Formation is present and resembles the Balintore Formation with its concentrations of *Rhaxella* spicules (Andrews and Brown, 1987; Stephen *et al.,* 1993).

When the sequence from the base of the Lias to the Balintore Formation is traced across the Inner Moray Firth a gradual thinning is observed from the Brora area eastwards across the Great Glen Sub-basin to the Central Ridge (Andrews and Brown, 1987; Underhill, 1991). This thinning continues across the Lossiemouth Fault and the Lossiemouth Sub-basin to the Moray coast (Figure 8). Thus, in this part of the Jurassic only the Great Glen Sub-basin was present, and maximum thickness occurs close to the Helmsdale Fault on the NW of the basin. There is no evidence that the Great Glen Fault had any significant effect in controlling sedimentation; from seismic data (Underhill, 1991) the sequence thickens into the Helmsdale Fault.

Late Oxfordian to Ryazanian

In the outcrop area covered by the guide this part of the succession comprises shales, siltstones, sandstones and boulder beds dominantly of Kimmeridgian age. Active synsedimentary faulting on the Helmsdale Fault and other faults in the Inner Moray Firth (Smith Bank Fault, Lossiemouth Fault) resulted in deposition of up to 3,000 m of strata which are thickest close to the downthrow side of the active faults (Figure 8). From Kintradwell to the north of Helmsdale the effects of synsedimentary fault movement on sedimentation can be examined in great detail, and are covered in the itineraries of Excursion 3.

The succession (Figure 2) and Excursion 3, (Figure 3.2) is at least 800 m thick. There is a general younging of strata northwards along the coast. Stratigraphic work on the ammonites (Bailey and Weir, 1932; Linsley, 1972; Brookfield, 1976; Wignall and Pickering, 1993) and palynology (Lam and Porter, 1977; Riley, 1980; Barron, 1989) indicates that the succession is probably continuous from *cymodoce* Zone of the Kimmeridgian to *albani* Zone of the Middle Volgian. Whilst there is some evidence of early Jurassic activity on the Helmsdale Fault (see above), the fault does not seem to have exerted a strong control on sedimentation until Kimmeridgian times, when the fault scarp formed a submarine topographic feature.

At Brora, little is known of the Upper Oxfordian rocks that overlie the Ardassie limestones due to lack of exposure. Borings at Ardassie Point indicate that bioturbated shales with thin sandstones deposited in a shallow marine environment are present. The first exposures to the north of Brora at Kintradwell are shales of *cymodoce* Zone which have interbedded boulder beds and slumps derived from a shallow shelf to the west. At some time in the late Oxfordian or early Kimmeridgian the fault became active, downthrow to the east was rapid, and sedimentation could not keep pace with subsidence. The result was the rapid creation of an exposed submarine fault scarp with a deepwater marine environment on the downthrow side of the fault, and a narrow shallow-marine shelf and shoreline on the upthrown side (Excursion 3, (Figure 3.3) and (Figure 3.17)). This shelf is not preserved but its presence can be deduced from the evidence of fauna, flora and clasts that were swept off the shelf into deep water to be preserved along with the open marine fauna of ammonites and belemnites (see Excursion 3).

In the region of Allt na Cuile and Lothbeg Point boulder beds are replaced by a porous quartzose sandstone interbedded with fissile siltstones and shales. The siltstones and shales contain ammonites of *cymodoce* Zone and are in part the lateral equivalents of the boulder beds of Kintradwell (Wignall and Pickering, 1993). Well-preserved leaves of land plants are found in association with the ammonites in this area, and provide evidence of the flora of the adjacent landmass. Van der Burgh and van Konijnenburg-Van Cittert (1984) recognised plants typical of brackish swamps (*Gleichenites cycadina*) and freshwater swamps (*Taxodiophyllum scoticum*) of a low-lying delta to be the dominant floral elements. Less abundant representatives of heath, moist lush vegetation and upland forest were also recognised. These sandstones (Allt an Cuile Sandstone) were derived from a delta area on the upthrown side of the fault which developed at a river mouth draining the Scottish landmass. The sandy delta deposits spilled over the fault line to form sandy submarine deposits in the deep water. Evidence of channeling, downslope sand movement and deposition from turbidity currents is seen. Vegetation swept out by floods became waterlogged and sank into deep water close to shore to be preserved along with the marine fauna. The water in which the sandy fan accumulated was deeper than local wave base, since wave-produced structures are absent, but bioturbation present in underlying shales and in some sandstones implies moderately shallow conditions. The Lothbeg Siltstone overlies the Allt na Cuile Sandstone, and is of *mutabilis* Zone age (Wignall and Pickering, 1993). Drifted land plants are common in these rocks and benthic faunas record an upward decrease in benthic oxygenation levels which is continued in the overlying Helmsdale Boulder Beds (Wignall and Pickering, 1993).

The rest of the Jurassic coastal sequence to the north of Helmsdale (Excursion 3) displays the interbedding of boulder beds, dark siltstones and shales which comprise the Helmsdale Boulder Beds. Close to the Helmsdale Fault chaotic deposits of rock-fall breccias are seen (e.g. Excursion 3, Itinerary 3) forming a strip up to a few hundred metres in width. Further from the fault, boulder beds are interbedded with dark fissile siltstones and thin pale sandstones. In some places giant boulders are seen, the most spectacular being the (wrongly named) 'fallen stack' at Portgower (Excursion 3, Itinerary 3). This clast of bedded Middle ORS flagstones is at least 30 m long, and must have fallen and slid into deep water from an exposed fault scarp greater than 30 m in height. Most boulder beds were deposited as matrix-poor debris flows and some can be observed to wedge out away from the fault. The blocks in the boulder beds frequently exceed the bed thickness and protrude above the bed top; lamination beneath the beds shows distortion caused by emplacement of the beds.

Thin sandstone beds within the dark siltstones contain plant debris and marine bioclasts which were probably deposited when storms battered the coastline and swept sand over the fault scarp from the shallow shelf (Excursion 3, (Figure 3.3)). In the Helmsdale area the boulder beds have a matrix of bioclastic debris including fragments of bivalves, echinoids, brachiopods, serpulid worms and other shallow marine organisms. Coral colonies (*Isastraea*)are also present, and some clasts were bored by bivalves prior to incorporation in the boulder beds. In this area a rocky shelf with high organic productivity bordered the fault scarp, but little detrital sand was available, in contrast to conditions to the south at Kintradwell where boulder beds have a sandy matrix.

Movements on the fault must have resulted in severe earthquakes which probably triggered the slumps that are seen in both the Kintradwell and Helmsdale boulder beds. Sandstone dykes (Excursion 3, Itinerary 1) were formed when sand, liquefied by shock, was injected into fractures. Pickering (1983, 1984) has described some of the sedimentological detail of these deposits.

Along the line of the fault there are distinct changes in clast types in the Boulder Beds. These were discussed by Bailey and Weir (1932) and have been investigated by MacDonald (1985, and Excursion 3 in this guide). In the south of the area some reworked Jurassic material (sand and pebbles) is present together with clasts of cross-bedded sandstones of fluvial origin, which, on the basis of petrographic comparisons, are probably derived from the upper ORS. From Portgower to Helmsdale clasts of Middle ORS flagstones dominate. On the upthrow side (footwall) of the fault in the early Kimmeridgian, it is possible that poorly consolidated Jurassic strata rested directly on Upper ORS fluvial sandstones which overlay Middle ORS flagstones. At present, Moine psammites, Lower ORS and Helmsdale Granite occur to the west of the fault. Clearly these rocks were not unroofed, nor were they exposed on the Helmsdale Fault scarp in the Kimmeridgian, since no clasts of these rocks occur in the boulder beds. Thus considerable post-Kimmeridgian movement has taken place on the Helmsdale Fault.

Whilst there may still be minor differences in interpretation, the general story of fault-controlled sedimentation of the boulder beds follows the classic interpretation of Bailey and Weir (1932) which has been endorsed by more recent work (Crowell, 1961; Linsley, 1972; Pickering, 1984; MacDonald, 1985; Wignall and Pickering, 1993; Underhill, 1994). Earlier interpretations of the origin of the boulder beds include crush breccias (Murchison, 1827), penecontemporaneous coastal erosion (Cunningham, 1841) ice transport (Ramsay, 1865), violent floods from rivers (Judd, 1873), screen with an ice foot (Blake, 1902), and falls from steep hillsides into the sea (Woodward, 1911). Hugh Miller came very close to the current opinion, recognising the Devonian fish in the clasts, which he considered had been derived from a nearby mountainous area (Miller, 1854) and he also recognised the role of earthquakes in the formation of the sandstone dykes (Miller, 1859). The 'fallen stack' at Portgower was first interpreted as such by Blake (1902) and this was repeated by Macgregor (1916), at which time steep cliffs or hillsides were envisaged as the source of boulders. Bailey and Weir visited the area in 1930 and 1931 following earlier realisation by Bailey of the true origin of the boulder beds. Their careful fieldwork and masterly exposition ended major speculation on the origin of these beds. Bailey and Weir acknowledge the help with fieldwork of two students of the Glasgow honours class — A. Lamont and J.G.C. Anderson.

It is unfortunate that the boulder beds cannot be followed for a greater distance away from the fault. Twenty kilometres offshore at Beatrice the succession is dominated by shale with only thin sand beds; it is probable that the debris flow beds only extend for a few kilometres offshore.

8. Cretaceous

No undoubted Cretaceous strata occur onshore in situ in the area covered by this guide, but Lower Cretaceous crops out on the seabed over large areas of the Inner Moray Firth. A summary of the Cretaceous history of Scotland is provided by Harker (2002). Active faulting in the Inner Moray Firth was a major control on deposition and it is probable that the Helmsdale Fault was still active. The Lower Cretaceous is over 750 m thick within 10 km of Wick, but the axis of sedimentation has now moved away from the line of the bounding Helmsdale–Wick fault system. The thickness distribution of Lower Cretaceous does not mirror that of the fault-controlled Upper Jurassic and it is clear from isopach maps that different faults were active (Andrews *et al.,* 1990, (Figure 31), (Figure 34). An unconformity is generally recognised beneath the Lower Cretaceous.

The deposits are of fine to coarse sandstones and dark shales and mudstones. Sandstones deposited on the downthrow (hanging wall) sides of faults are generally interpreted to be of submarine fan origin, but sandstones with a marine shelly fauna were probably typical of shallow areas, particularly around the basin margins. It is probable that northern Scotland was still emergent and acting as a source of sand supply to the Inner Moray Firth.

The Upper Cretaceous Chalk Group is at seabed on the downthrow side of the Wick Fault only 20 km offshore (Andrews *et al,* 1990). The Cenomanian transgression resulted in marine inundation and it is probable that, at times of highest sea level, northern Scotland was totally submerged or at least reduced to small islands. Marginal glauconitic sandstone 'Greenland' deposits occur in the Inner Moray Firth and are overlain by chalk and marl lithologies. Minor unconformities and subsequent onlap within the Upper Cretaceous of the Moray Firth reflect changes in sea level. Thickness of the Upper Cretaceous is controlled by the position of pre-existent basins, and by continued movement on the Wick and Banff fault systems.

Onshore evidence of Cretaceous strata is limited to glacial erratic material scraped off the floor of the Moray Firth and deposited onshore by ice moving NW over Caithness and SE over Buchan. Thus, a large Lower Cretaceous sandstone erratic (Tait, 1912) at Leavad in Caithness which contained a shelly fauna in calcareous concretions formed the basis for a sand quarry. It is not entirely clear whether the erratic was a single intact block or a composite broken mass. Numerous smaller Cretaceous erratics, particularly concretions from Lower Cretaceous sandstones and flints from the Upper Cretaceous, have been recorded in Caithness.

The only *in situ* occurrence that might be of Cretaceous age is a slice of fossiliferous sandstone within the Helmsdale Fault zone north of Helmsdale (Excursion 3, Itinerary 4).

9. Tertiary

No Tertiary deposits are preserved in the area, but it is probable that early Tertiary fluvial and deltaic deposits were present in the Inner Moray Firth. Sediments were derived from the Highlands by rivers draining the tilted late Cretaceous marine planation surface which was created by Upper Cretaceous marine transgression. Opening of the N. Atlantic, and volcanic activity on the west coast (summary in Bell and Williamson, 2002) resulted in post-rift basin collapse in the North Sea and tilting of the old erosion surface due to rifting on the west coast of Scotland. The evidence for the previous existence of an early Tertiary delta in the Inner Moray Firth is preserved as delta-derived slope facies and deep-water sandstones in the Outer Moray Firth and Central Graben (summary in Knox, 2002). Uplift in the Inner Moray Firth, for which evidence is seen along the Great Glen Fault (Underhill, 1991; Thomson and Underhill, 1993), resulted in reworking of the fluvial to deltaic system and a shift of deltaic facies to the Outer Moray Firth. Data presented by Hurst (1982), and Pearson and Watkins (1983) using clay minerals to elucidate burial history indicate that up to 1 km of section was probably removed by Tertiary erosion in the Inner Moray Firth; an unknown proportion of this section was probably early Tertiary in age. The land areas over which Tertiary sediments were derived became deeply weathered, particularly in the sub-tropical climate of the early Tertiary, and again in the Miocene. Relics of Tertiary deep weathering are common in the Buchan area to the south of the Moray Firth (Kneller, 1987) but most have been stripped off by glacial erosion in the area of this guide, although evidence of deep weathering is still preserved in the Helmsdale area (Boulton *et al.,* 2002). Within Tertiary time there were several phases of regional tilting and many transgessive/regressive episodes. Remnants of tilted planar erosion surfaces in northern Scotland are ascribed to such events. The surfaces are attributed to marine planation by some authors whilst others consider them to be of subaerial origin.

10. Quaternary

It is difficult to unravel the record of growth and decay of the Quaternary ice sheets that were responsible for moulding much of the scenery of the Highlands. An excellent overview covering the whole of Scotland is given by Boulton *et al.* (2002), and the earlier work of Charlesworth (1956) and Sisson (1968) is also of interest. For specific field evidence relating to Caithness, and a historical summary, the observations of Omand (1973) are most useful. The difficulty with interpretation on land is due to the fact that the last glaciation, in the late Devensian and culminating about 20,000 years BP, removed or masked much evidence of earlier glacial periods.

In Caithness there is evidence of earlier glacial episodes even if the absolute ages cannot be determined with certainty. Omand (1973) recognised an early till (Dunbeath Till) of local derivation and lacking shells. This is overlain by a Shelly till (Lybster Till) which contains molluscan shells of marine origin, and locally abundant Mesozoic glacial erratics derived from the bed of the Moray Firth. The most celebrated erratic is the Lower Cretaceous sandstone erratic at Leavad (Tait, 1912) which was apparently 220 x137 m in area and up to 8 m thick. Other erratics include Jurassic lithologies, similar to those at outcrop, and flints of Upper Cretaceous origin.

In Buchan, to the south of the Moray Firth, similar Mesozoic erratics and shelly boulder clay were also derived from the Moray Firth. Thus, it is postulated that an ice dome existed in the Moray Firth at this time with ice flowing away from the centre of the dome, to the NW over Caithness and SE over the Buchan area. Further evidence for NW ice flow in Caithness is provided by a train of erratics of Sarclet Conglomerate extending from Sarclet NW to the Thurso and Dunnet areas on the north coast. This ice movement phase is thought to be older than 40,000 years on the basis of carbon dating (limit of method) of shell material, and could possibly be as old as a cold phase about 70,000 years ago.

The westward limit of the shelly till follows a line from Berriedale to Reay. To the west of this line, an upper till (Reay Till) of local derivation is found which may have been contemporaneous with the shelly till. The ice transporting this till appears to have flowed to the E and NE and been deflected northwards by the ice responsible for deposition of the shelly till.

The last glacial episode in Caithness in the Late Devensian, about 20,000 years ago, is not associated with extensive till deposits, and it is possible that Caithness lay at the margin of the ice sheet that covered most of Scotland. The Moray Firth ice dome was not re-established at this time and ice flowed freely into the Moray Firth. Moraines and fluvio-glacial gravels that overlie the local (Reay) and shelly till in Caithness represent marginal deposits of the ice sheet. The major valleys such as Langwell and Berriedale contain moraines of local material probably left from small valley glaciers which may have been fed from small, local ice accumulations. For example, glaciers in valleys at Dunbeath, Berriedale and Langwell may have been fed from a snowfield on Knockfin.

Periglacial processes in Caithness were severe, often disturbing the top metre of drift sections by frost action. The ice-smoothed landscape was further affected by solifluction, further filling and smoothing the valleys. The general undulating topography of Caithness with its cover of impermeable boulder clay was ideal for establishment of extensive post-glacial lakes and subsequent peatbogs.

Although there are no well-marked shorelines in the north of the area, relics of raised platfoms can be identified south of Helmsdale, and impressive river terraces are present, particularly on the Brora River. The fine cliffs of the east Caithness coast have a history dating back beyond the Late Devensian glacial maximum. It seems probable that they were created by the outward flow of ice from the earlier Moray Firth ice domes. The ice easily eroded the soft Mesozoic strata, but was less effective at removing the Helmsdale Granite and Devonian strata on the NE side of the Helmsdale Fault. Perhaps the ice was initially deflected NE up the coast prior to over-riding Caithness as the ice accumulation developed. The cliffs are preserved because the land-derived Late Devensian ice sheet did not cover them, only sending minor glaciers down the major valleys which cut the coastal cliff line.

11. Economic geology

This area is remarkable for the variety of geological features that have been, or still are being exploited. Interesting historical information can be found in Read *et al.* (1925) and Crampton and Carruthers (1914), whilst more recent information is given in Johnstone and Mykura (1989) and Beveridge *et al.* (1991). Much of the following information is based on these accounts.

The flagstone industry

The effects of the exploitation of the flagstones of the Middle Old Red Sandstone of Caithness have left a unique legacy to the whole county. The upright slab walls of field divides, large roof flags on croft outhouses, and the general building construction are unique in Britain. The suitability of the flagstones for building has been recognised from prehistoric times — the most famous examples being the Stone Age constructions of Skara Brae and Maeshowe in Orkney. Most older buildings are made of flagstones, usually from local quarries. For example, coastal quarries at South Head, Wick, provided much of the stone with which the town is built. The 'export' of flagstones from Caithness started in 1825 to many cities and towns, such as Torquay, Newcastle, Glasgow and London in the UK, but Caithness flags can also be seen in Hamburg, New York, Melbourne, Calcutta, Bombay, and Rio de Janiero. Crampton and Carrruthers (1914) provide an interesting historical account of the industry. In the last years of the 19th century export ran at around 20,000 tons/annum with a value of around £1/ton and 400–500 people were employed in the industry. Crampton and Carruthers (1914) record that the decline in the industry which set in around 1908 was due to the increasing use of concrete for pavements; thus by 1911 production was down to about 6,000 tons worth only £4,150, with 145 people employed. The industry collapsed after the First World War and virtually all quarries were abandoned, the industry clinging on at Spital prior to recent expansion. The best quality paving slabs were obtained from a number of quarries which included the cliff-top quarry at Ness of Litter near Holborn Head, Spital Quarry and quarries at Castletown where the Castlehill Flagstone Trail provides an insight into the history of the Industry. Lesser quality flags were used for farm buildings and the characteristic Caithness field walls of upright slabs.

Achanarras Quarry was worked for thin micaceous flags that were used as roofing slates. The slates were difficult to 'hole' and slate working had been abandoned by the time Crampton and Carruthers wrote the Caithness Memoir. Evidently the Achanarras fish bed itself was used for slates, since I have seen a *Rhamphodopsis* from the central part of the fish bed preserved on a roof slate. Slates were also produced from a quarry named Whitemoss, some 3.5 miles SE of Thurso, which would place it near Weydale (Specimens in BGS Collection). Slates were produced until recently on a small scale at Achavrole near Halkirk, particularly for maintenance of historic buildings such as St Magnus Cathedral on

Orkney, but the quarry has been infilled with waste from Calder Quarry.

The flagstone industry has revived in recent years, with current (late 2008) traditional working of flagstones at Spital Quarry, and at Achscrabster. Flagstones have been worked recently at Cairnfield Quarry, Weydale, and at Calder Quarry, but these two quarries are currently inactive apart from small-scale working for local use. Increasing use of natural stone in our cities has resulted in considerable output of flagstones in the past 10 years, and examples of recent use can be seen in Glasgow, Edinburgh, Aberdeen, Newcastle and many other places. There is also considerable production of crushed rock for roads and building purposes.

Sand and gravel

There are numerous small sources of sand and gravel in the area, usually working fluvioglacial material. Beach and blown sand has also been exploited in the past, but destruction of beach and dune systems is no longer acceptable. The sand quarry that existed in the Lower Cretaceous erratic at Leavad produced sand that was used as an abrasive in the machines used to cut the flagstones (Crampton and Carruthers, 1914).

Extensive sand and gravel deposits are present south of Helmsdale on the low-lying coastal platform. Sand and gravel has been worked on a small scale for many years from the low coastal platform near Loth.

Limestone

The importance of lime for agriculture led to use of many of the fish bed laminites as a local source. Examples are the limestones at Port of Brims and at Baligill (Excursion 5), where well-preserved lime kilns can be seen. Shell sand from beaches was also burnt for lime.

Building stones

A great variety of rocks have been used for the older buildings in the towns of the area. The rock was obtained locally and seldom transported more than a few miles. Thus, Golspie is dominated by red sandstones of the local Old Red Sandstones, and Brora by white to grey sandstones of the Clynelish Quarry Sandstone from Clynelish. Some of the best blocks of Clynelish Quarry Sandstone can be seen in the walls of Dunrobin Castle.

In Caithness numerous local flagstone quarries were used to supply stone for general building work. The variety of building materials, such as sandstones from the Wick Flagstones, the John o' Groats Sandstone and Dunnet Sandstone have all been used, giving subtle differences to the colour and architecture of the towns.

Coal

The earliest reference to coal at Brora dates from 1529 (see Owen, 1995), and Brora Coal was first mined in 1598 when the Countess of Sutherland opened a coal pit. Her son, the fifth Earl of Sutherland, is recorded as re-opening the works in 1634 (Flett *in* Lee, 1925) and four or five pits were sunk, in one of which 15 men were killed by a roof-fall. A John Williams worked the coal for five years starting around 1764. These early pits were near the shore on the south side of the river, and they exploited coal to a depth of about 100 ft (c.30 m). The coal was used to evaporate salt water in salt pans built near the pits. 'Salt Street' is a reminder of this industry.

About 1810 a shaft was sunk on the north bank of the Brora River and reached coal at 259 ft (c.78 m). From the account quoted by Lee (1925), this appears to be the same shaft that was being used in the 1920s. By this time another pit on the south side of the river was already disused.

In 1956 the N.C.B. estimated reserves of coal at over 12 million tons and suggested testing of the Clynelish and Northern fault blocks with boreholes. The reports of Ewing (1956, 1958) provide information on borings and the structure of the coalfield. In 1966 the Highlands and Islands Development Board put down five boreholes and proved the presence of mineable coal in the inland blocks (Berridge, 1967). An inclined adit was opened in 1969, but the mine ceased production in 1974 and the workings were abandoned in 1975.

The coal seam was generally about a metre thick with a dirt parting in the middle containing a band of pyrite. The coal burnt well, but with an objectionable sulphurous odour, and left a fine white ash that 'every breath of air sent floating over carpets and furniture' (Miller, 1859). Thus, it was not popular with housewives as a house coal. The coal was also prone to spontaneous combustion when exposed to air and damp due to the presence of pyrite. It was the spontaneous combustion of a cargo sent by John Williams to Portsoy which lost him customers who were afraid of such a dangerous cargo! Murchison (1827) recorded a production of 5–6,000 tons/ annum from 1814, and in 1910 the production was similarly 6,000 tons. In the 1920s about 30 tons/day were raised with the coal being used in the brickworks and Brora Wool Mill, as well as for domestic consumption. The site of the coal mine has now been landscaped. The Brora Coal is extensive offshore and is present in the Beatrice Oilfield wells, but there are no longer any exposures of the coal in the Brora area. An excellent illustrated history of coal mining at Brora by Owen (1995) provides further information on the industry.

Brick clay

The Brora Brick Clay of the Brora Argillaceous Formation was formerly dug on the north side of the Brora River for brickmaking, but the pit has now been filled, and other exposures have been landscaped along with the site of the coal mine. Local bricks stamped 'Hunter-Brora' were made from the brick clay, and can sometimes be seen on the foreshore at Brora, generally derived from dumped builders' waste.

Oil

On a clear day the production platforms of the Beatrice Oilfield can be seen from the shore between Brora and Wick. This is the only UK producing oilfield visible from shore, lying only 14 miles offshore from Lybster. The field was discovered in 1976 by Mesa Petroleum with their first exploration well on block 11/30. It was named Beatrice by T. Boone Pickens, the president of Mesa Petroleum, after his wife. Oil was found in Jurassic sandstones ranging from Lower to Upper Jurassic. The main reservoir (the 'A' sandstone) is of Middle to Upper Jurassic age and is very similar in character to the Brora Arenaceous Formation. However, the sandstones are not the same age, the Brora Sandstone being younger than the 'A' Sand. Production also comes from the 'B' sandstones which are the time equivalents of the Brora Roof Bed, and from sandstones equivalent to those in the Brora Coal and Dunrobin Bay formations.

The oil produced is a low sulphur, paraffinic crude with a high wax content (17%) and a high pour point (24°C). It differs from normal North Sea crude, which was largely sourced from organic-rich Kimmeridgian shales, and thus the source of Beatrice oil has given rise to considerable speculation. The Kimmeridge shale is usually immature in the Inner Moray Firth (not buried deeply enough to generate hydrocarbons) and is also not as rich in organic oil-prone material as in areas where it is the source of oil. A source within the Middle Jurassic is possible, particularly the shales of the Inverbrora Member of the Brora Coal Formation which are in part extremely rich in organic material (>25%) and approach the consistency of oil shale. Distillate yields of 32 and 26.5 gallons/ton have been recorded. Although these shales are only marginally mature at Brora, they are more deeply buried to the north and could have provided oil to charge the Beatrice Oilfield by updip migration. Organic geochemical data are indicative of partial sourcing of Beatrice oil from the organic-rich flagstones of the Middle Devonian (Duncan and Hamilton, 1988; Peters *et al.,* 1989), which were deeply buried in the Wick Basin in the Mesozoic (Trewin, 1989).

Production of Beatrice Oilfield started in 1981 with initial reserves calculated at 476 million barrels of oil in place with 162 million recoverable (Linsley *et al,* 1980). Production peaked at around 50,000 barrels/day in 1984. Ultimate recovery was downgraded to 146 million barrels by 1990 (Stevens, 1991), of which 126 million barrels had been produced by the start of 1992. Despite the prediction in 1992 from BP that the field would not last beyond the Millennium (B.P. pers. comm. January 1992), it is still producing in 2009, and is now operated by Ithaca Energy, who have found new oil-bearing structures in the area. The Polly accumulation lies east of Beatrice within drilling range of an existing Beatrice platform, and Jacky, 10 km NE of Beatrice, started production in April 2009. Ithaca Energy predict combined production from Beatrice and Jacky to be 10,000 barrels/oil/day in 2009.

An onshore exploration well near Lothbeg Point (Sutherland No. 1) in 1980 proved unsuccessful, but small new fields called Lybster and Knockinnon have been discovered close to the Caithness shore. Lybster will be produced from wells drilled from land to the offshore field, the first well being completed in 2008, but there has been no resulting prodution.

The Middle Old Red Sandstone lacustrine deposits, particularly the fish-bed lithology, are rich in oil-prone organic matter (Marshall *et al.,* 1985; Duncan and Hamilton, 1988). The potential of these rocks for hydrocarbon accumulations has been discussed by Trewin (1989) who concluded that oil was unlikely to be found reservoired onshore in Devonian strata, but might be found offshore where Middle ORS is deeply buried by Mesozoic strata, and better possibilities exist for sealing any oil migrated from the Devonian into younger rocks. Solid hydrocarbons are sometimes found associated with vein deposits in the flagstones, the hydrocarbons being derived from maturation of organic matter in the flagstone (Parnell, 1983). Minor mobile hydrocarbons were present in sandstones encountered during drilling at Cairnfield Quarry, Weydale (NHT pers. obs., 2004).

Gold

The short-lived gold rush of 1869 was started by the finding of alluvial gold in the Kildonan and Suisgill burns, which are tributaries of the Helmsdale River (Rice, 2002). Details and references are given in Excursion 6, to which the reader should refer. The gold originates from the migmatised Moine metasediments and has been concentrated by glacial erosion and reworking of the glacial debris by the streams. Deep weathering prior to glaciation may have aided the release of the gold. The original diggings were stopped by the Duke of Sutherland on account of the damage that was being done to the fishing in the Helmsdale by the silt carried from the diggings. (The diggers may also have been partial to salmon and venison.)

Undoubtedly gold remains in the area, washed down into the gravels of the Helmsdale. However, it is unlikely that a short-term alluvial working would benefit the local community, particularly if the salmon fishing was affected. The gold is still panned on a recreational basis with the permission of the estate, and this appears to be the best economic use of the resource at present.

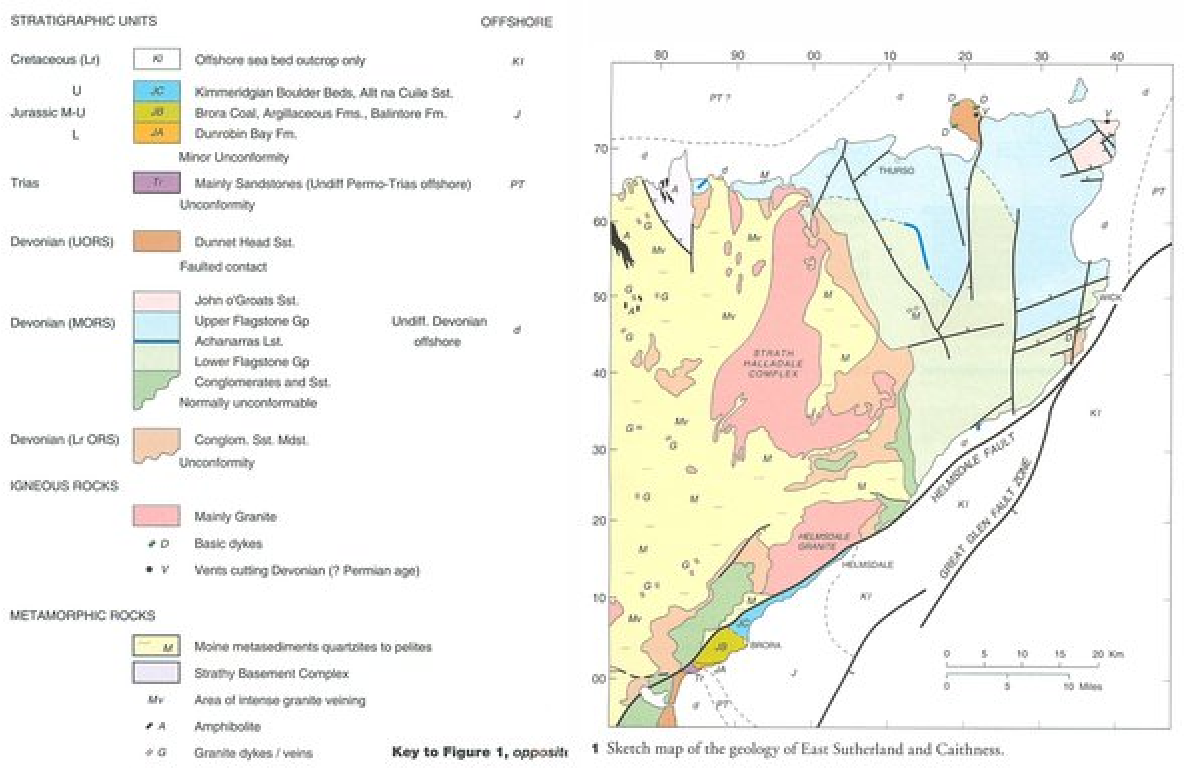
Metallic ores

There are few mineral veins in the area, but a lead/zinc vein was worked on a small scale near Achanarras, and thin veins are sometimes found in the spoil material at Achanarras Quarry. A copper-bearing vein is said to have been worked on the coast south of Old Castle of Wick in the 15th century (Crampton and Carruthers, 1914). Tweedie (1979) reported minor uranium mineralisation from the Helms-dale Granite and also noted Cu–Mo mineralisation in the Ord Burn. Rice (2002) describes the metallic ores from the area.

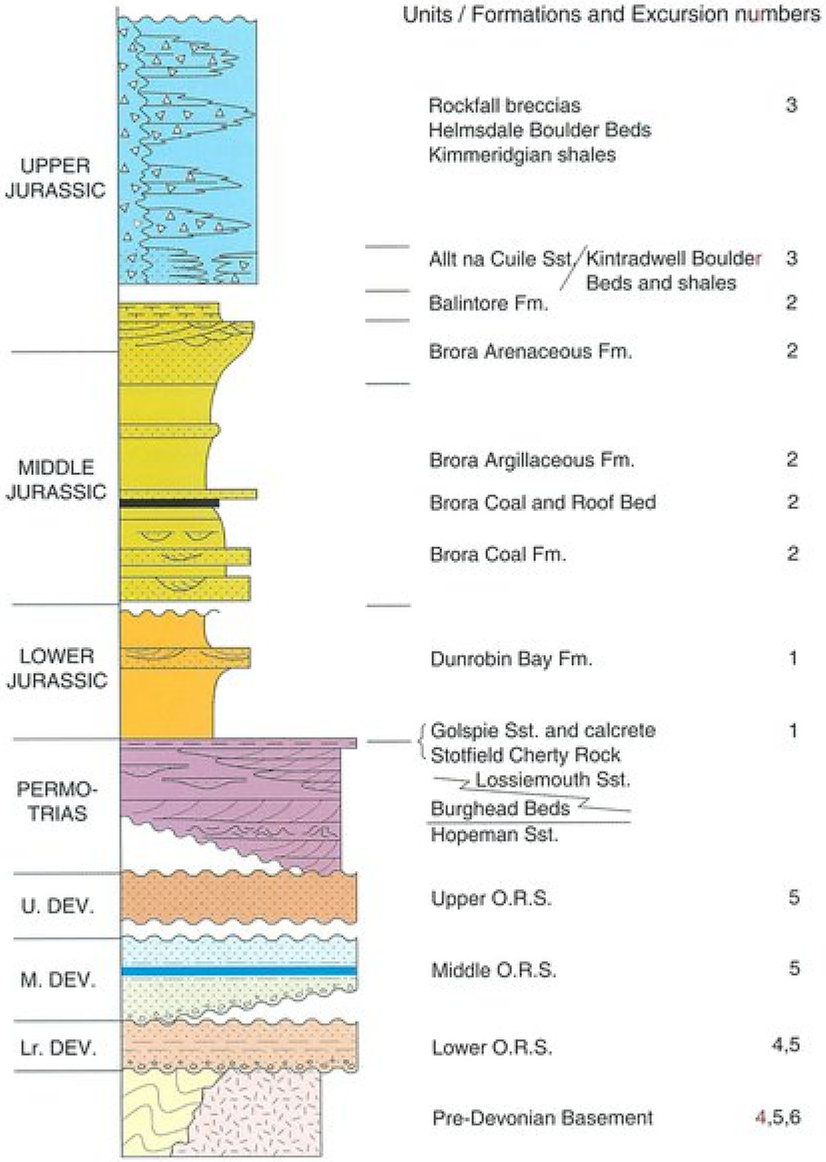
Non-metallic minerals

A vein of barytes over 6 ft wide at Ray Geo near Lybster has been worked for the mineral, and minor veins of barytes occur throughout the area, emanating from the Helmsdale Granite, which also has small veins of fluorite (Tweedie, 1979). Calcite veins are frequently seen, particularly in fractures adjacent to the Helmsdale Fault (Excursion 3, Itinerary 4) and cutting the Middle ORS flagstones.

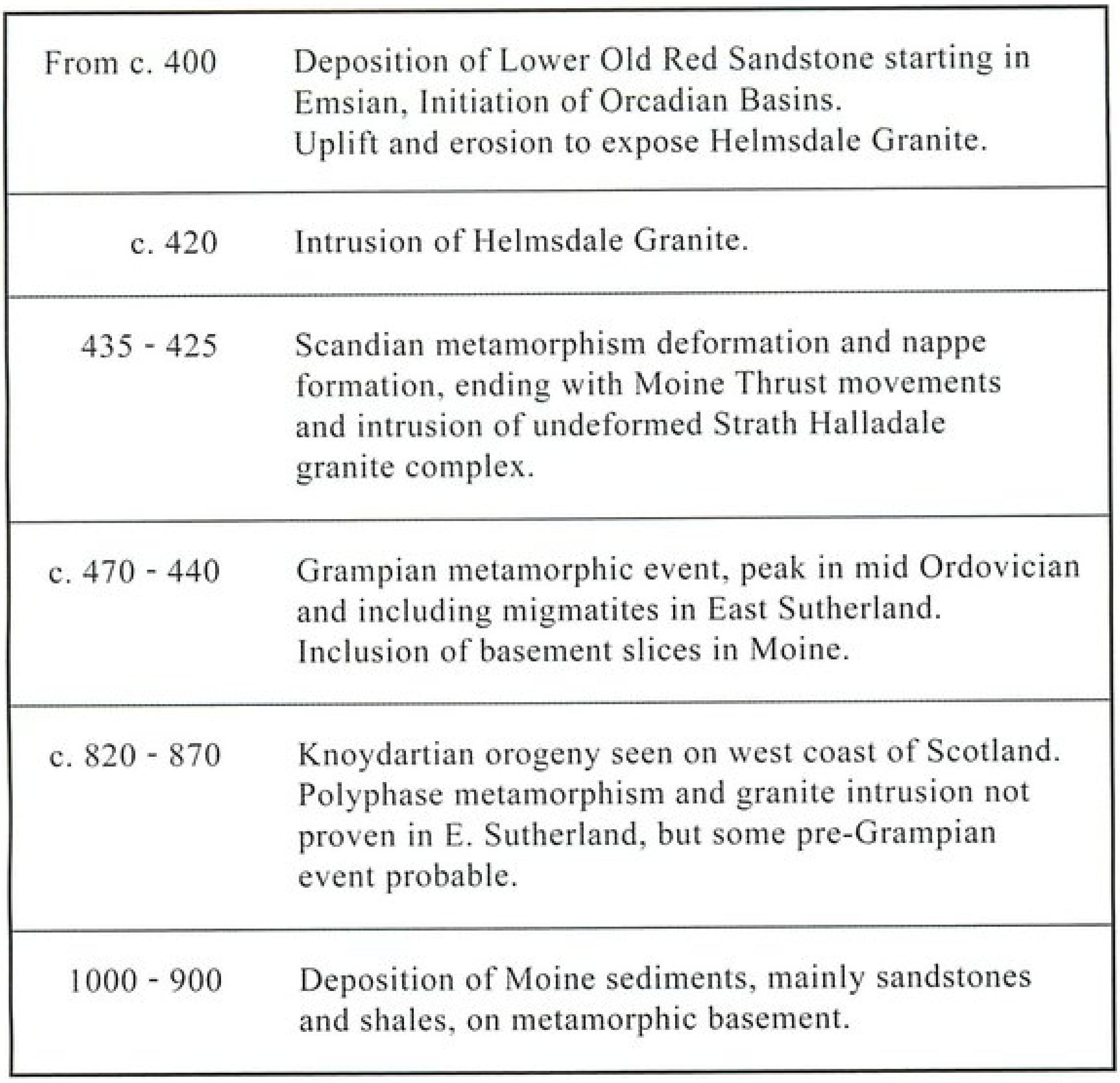
References



(Figure 1) Sketch map of the geology of East Sutherland and Caithness.

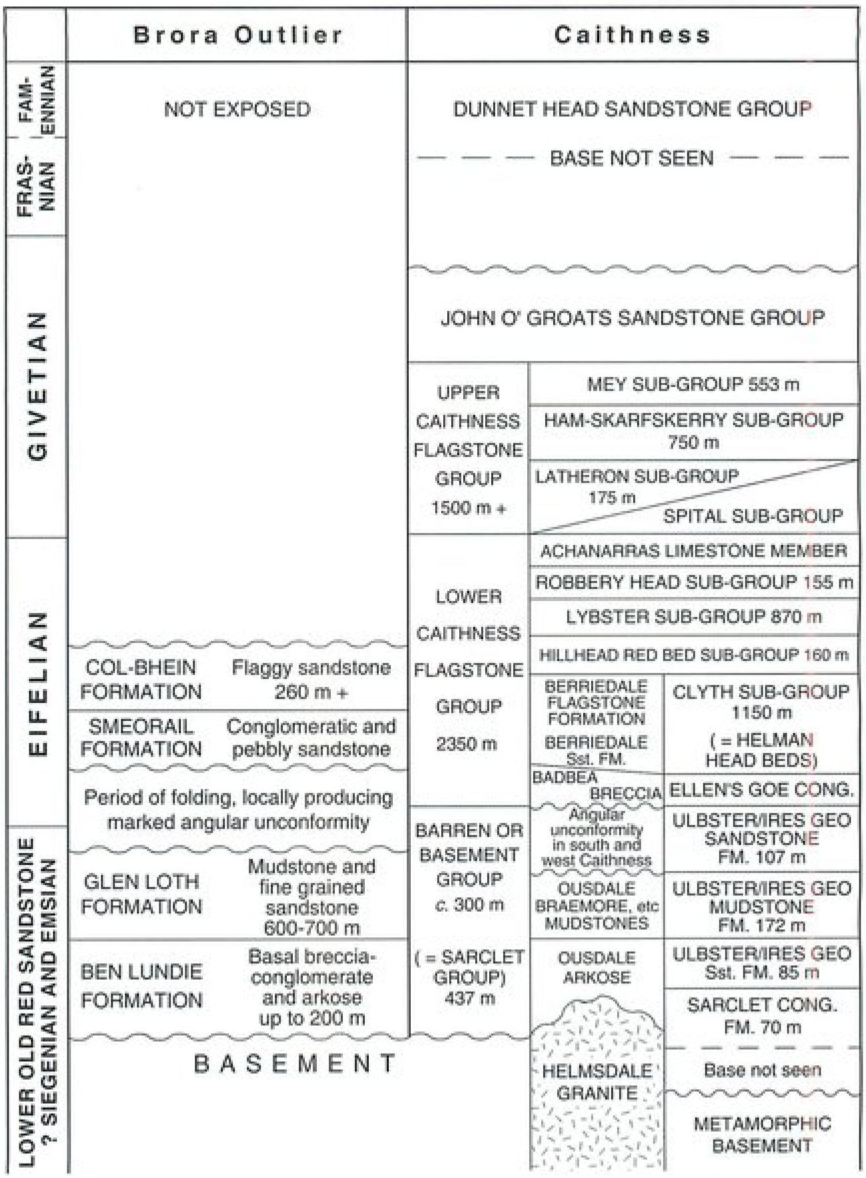


(Figure 2) Basic stratigraphic framework and relevant excursions.

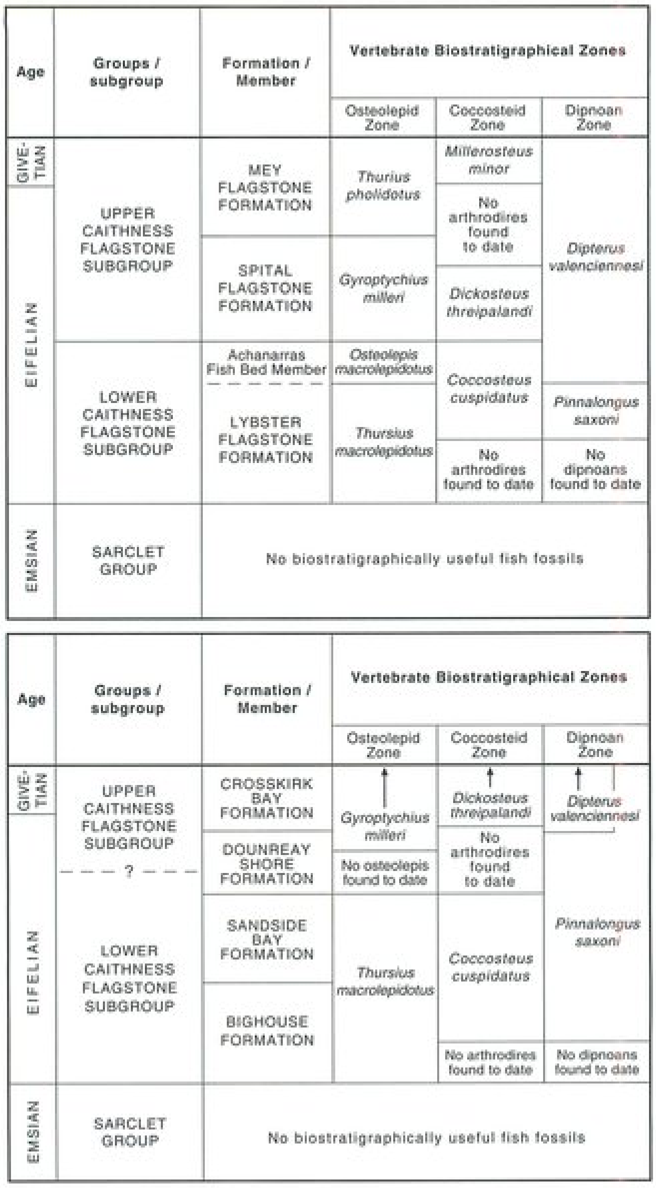


From c. 400	Deposition of Lower Old Red Sandstone starting in Emsian, Initiation of Orcadian Basins. Uplift and erosion to expose Helmsdale Granite.
c. 420	Intrusion of Helmsdale Granite.
435 - 425	Scandian metamorphism deformation and nappe formation, ending with Moine Thrust movements and intrusion of undeformed Strath Halladale granite complex.
c. 470 - 440	Grampian metamorphic event, peak in mid Ordovician and including migmatites in East Sutherland. Inclusion of basement slices in Moine.
c. 820 - 870	Knoydartian orogeny seen on west coast of Scotland. Polyphase metamorphism and granite intrusion not proven in E. Sutherland, but some pre-Grampian event probable.
1000 - 900	Deposition of Moine sediments, mainly sandstones and shales, on metamorphic basement.

(Figure 3) Sequence of events in pre-Devonian basement. Summarised from Strachan et al. (2002) and Trewin and Rollin (2002).



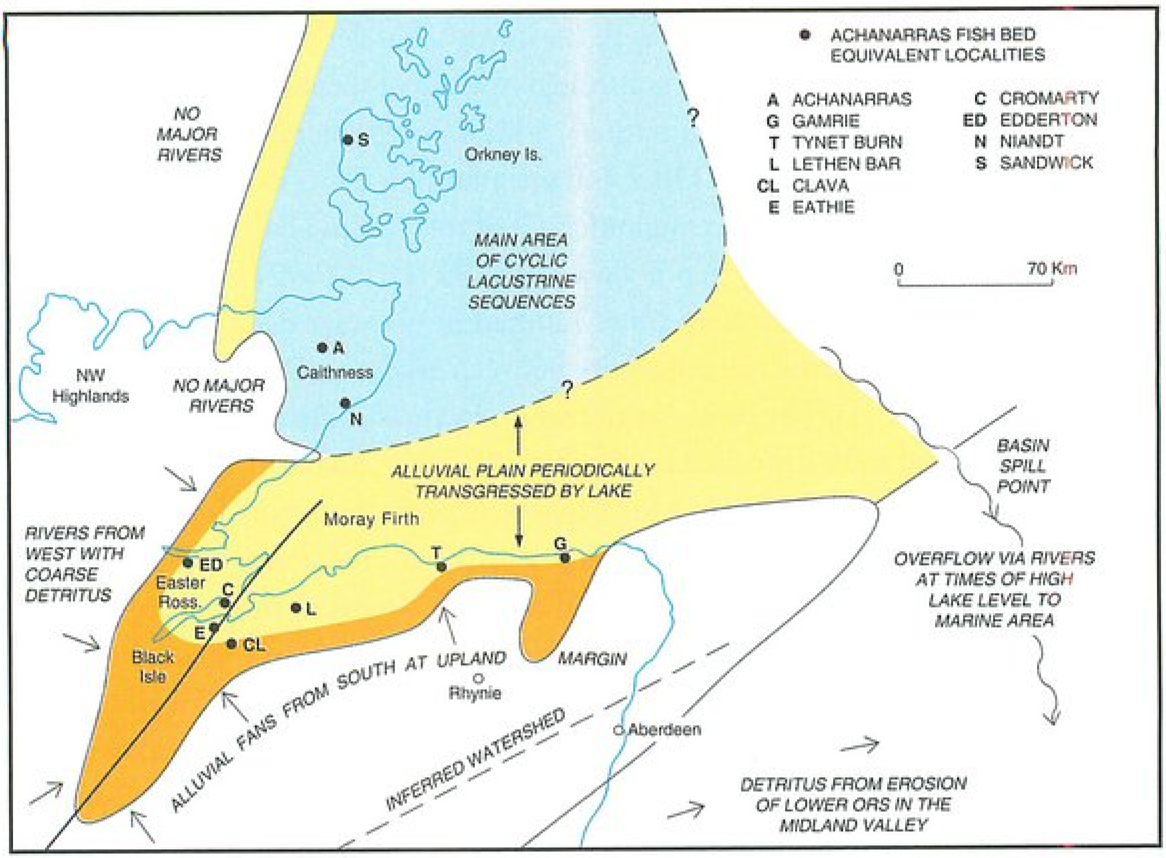
(Figure 4) Stratigraphic nomenclature for the Devonian in eastern and southern Caithness and the Brora region of Sutherland. Modified from Trewin and Thirlwall (2002).



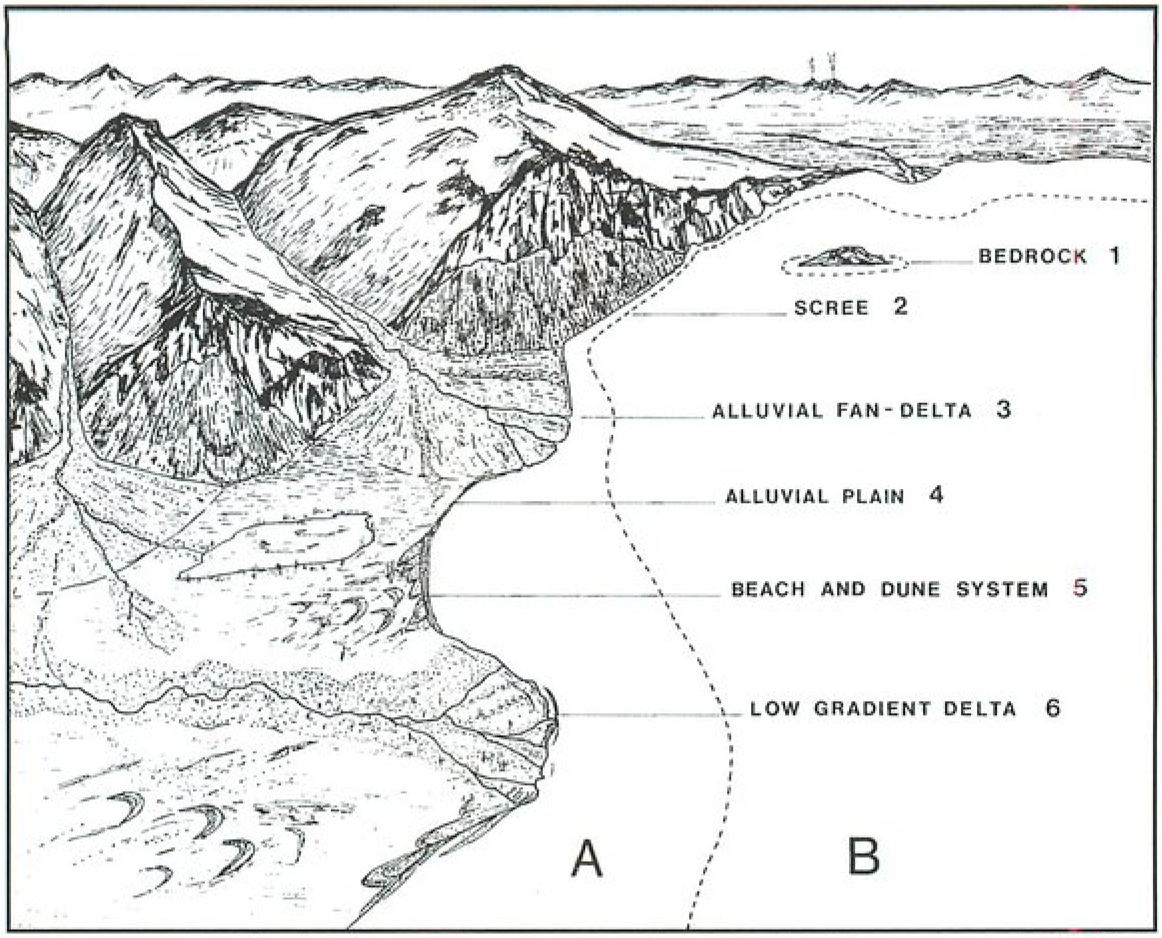
Age	Groups / subgroup	Formation / Member	Vertebrate Biostratigraphical Zones		
			Osteolepid Zone	Coccosteid Zone	Dipnoan Zone
GIVE-TIAN	UPPER CAITHNESS FLAGSTONE SUBGROUP	MEY FLAGSTONE FORMATION	*Thurius pholidotus*	*Millerosteus minor*	*Dipterus valenciennesi*
EIFELIAN				No arthrodires found to date	
		SPITAL FLAGSTONE FORMATION	*Gyroptychius milleri*	*Dickosteus threipalandi*	
	LOWER CAITHNESS FLAGSTONE SUBGROUP	Achanarras Fish Bed Member	*Osteolepis macrolepidotus*	*Coccosteus cuspidatus*	
		LYBSTER FLAGSTONE FORMATION	*Thursius macrolepidotus*		*Pinnalongus saxoni*
				No arthrodires found to date	No dipnoans found to date
EMSIAN	SARCLET GROUP	No biostratigraphically useful fish fossils			

Age	Groups / subgroup	Formation / Member	Vertebrate Biostratigraphical Zones		
			Osteolepid Zone	Coccosteid Zone	Dipnoan Zone
GIVE-TIAN	UPPER CAITHNESS FLAGSTONE SUBGROUP	CROSSKIRK BAY FORMATION	↑ *Gyroptychius milleri*	↑ *Dickosteus threipalandi*	↑ *Dipterus valenciennesi*
EIFELIAN				No arthrodires found to date	*Pinnalongus saxoni*
	— — — ? — — —	DOUNREAY SHORE FORMATION	No osteolepis found to date		
	LOWER CAITHNESS FLAGSTONE SUBGROUP	SANDSIDE BAY FORMATION	*Thursius macrolepidotus*	*Coccosteus cuspidatus*	
		BIGHOUSE FORMATION			
				No arthrodires found to date	No dipnoans found to date
EMSIAN	SARCLET GROUP	No biostratigraphically useful fish fossils			

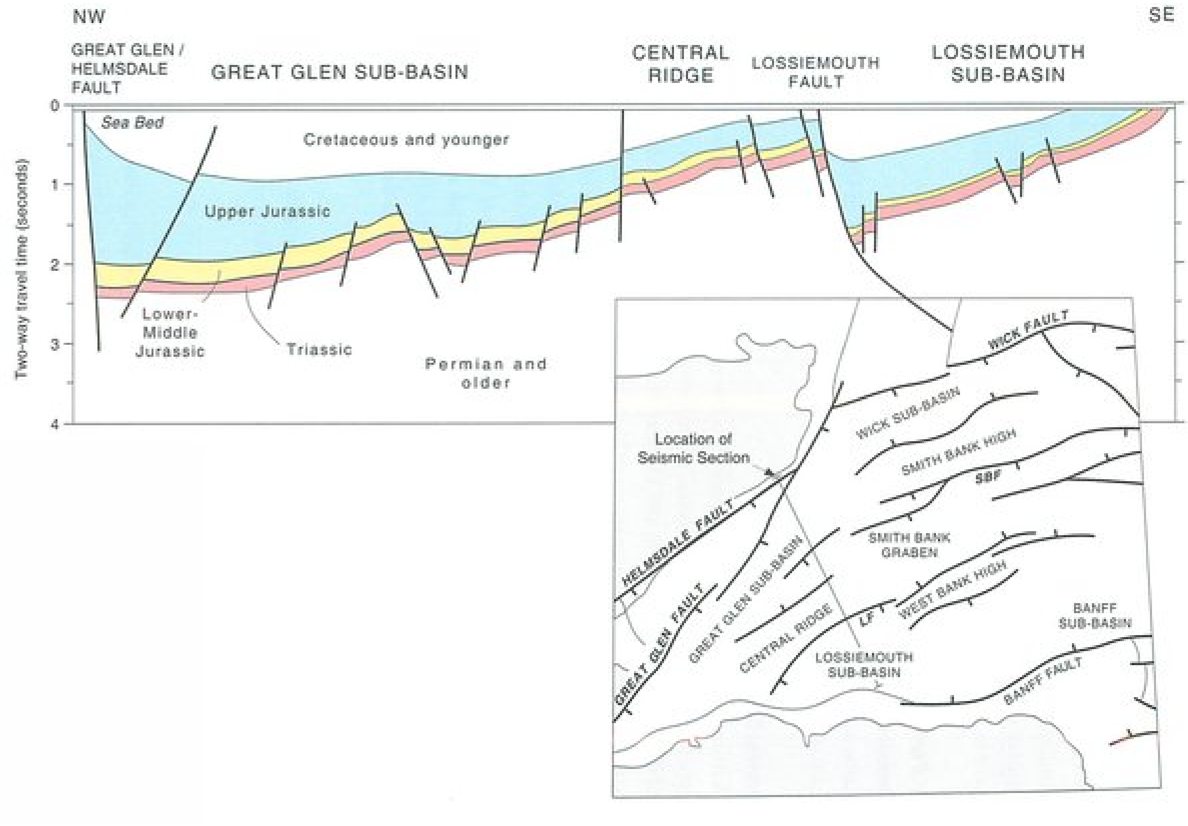
(Figure 5) Stratigraphic nomenclature for the Devonian in NW Caithness and the adjacent part of Sutherland showing correlation and fish faunas on either side of the Bridge of Forss Fault. (From British Geological Survey, 2005; Newman and den Blaauwen, 2008.)



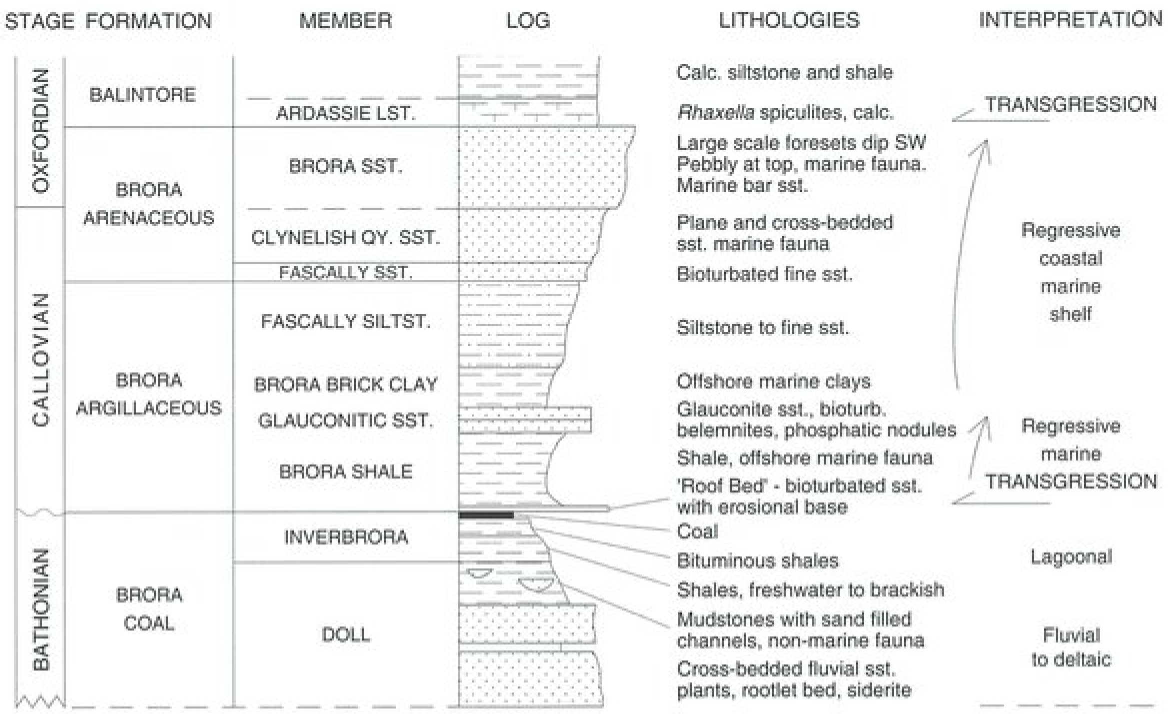
(Figure 6) Middle ORS palaeogeography of north-east Scotland reconstructed with 30 km post-Devonian dextral shift on the Great Glen Fault. Modified from Mykura (1991) and Hamilton and Trewin (1988).



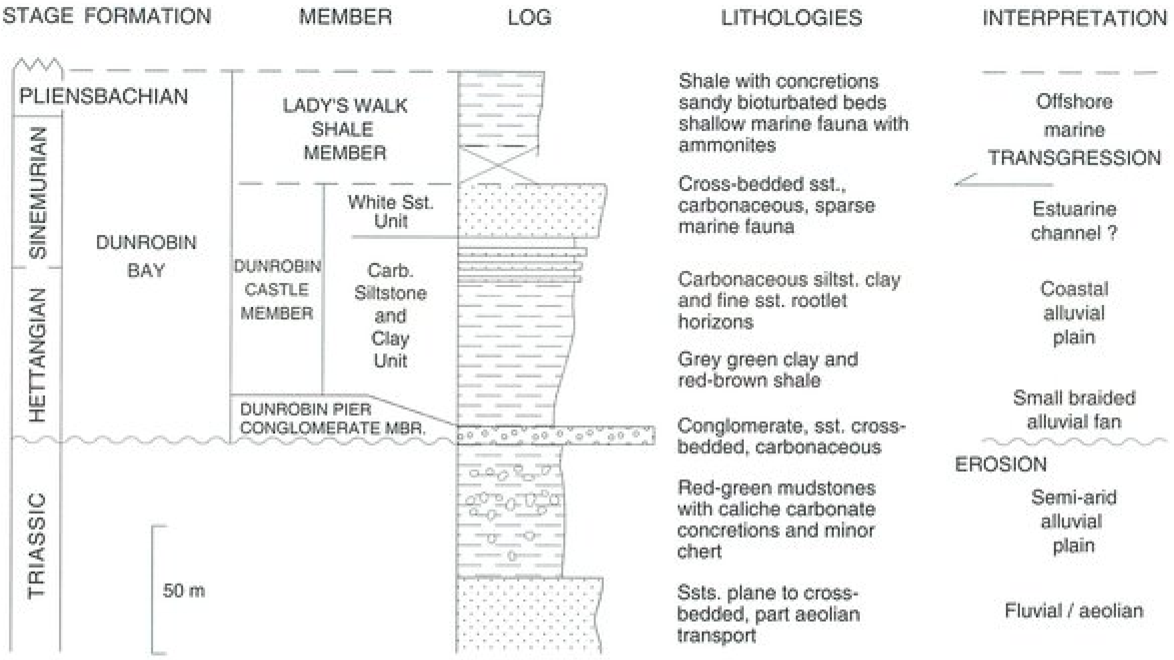
(Figure 7) Diagrammatic sketch of marginal situations to the Orcadian lake at a time of high lake level. Zone A represents shallow areas in which bottom conditions were oxygenated and area B the deeper lake where anoxic conditions existed beneath a thermocline. Modified from Trewin (1986).



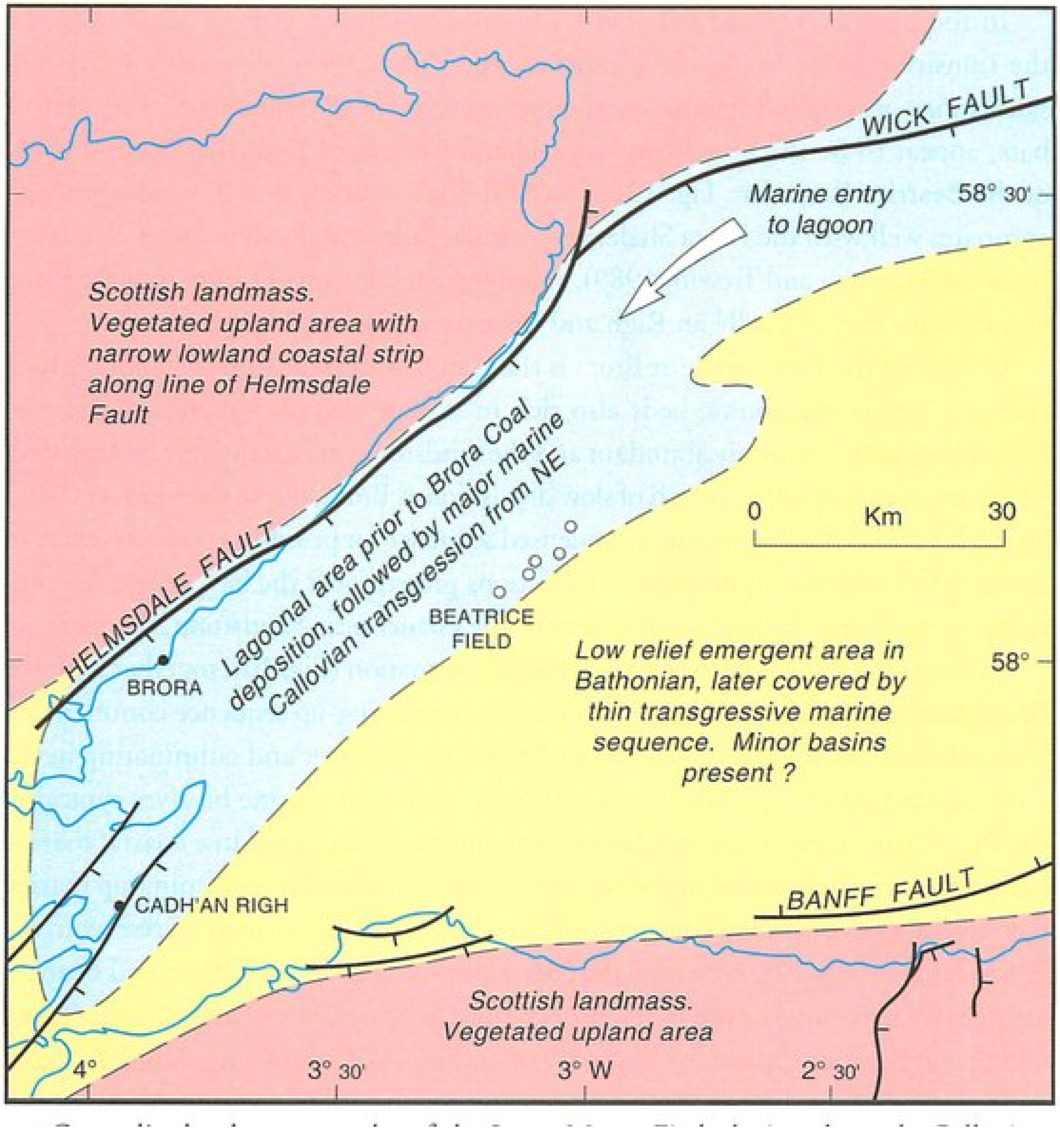
(Figure 8) Interpreted seismic cross-section of the Inner Moray Firth Basin (Modified from Andrews et al., 1990). Line of section shown on inset basic structural map of the basin.



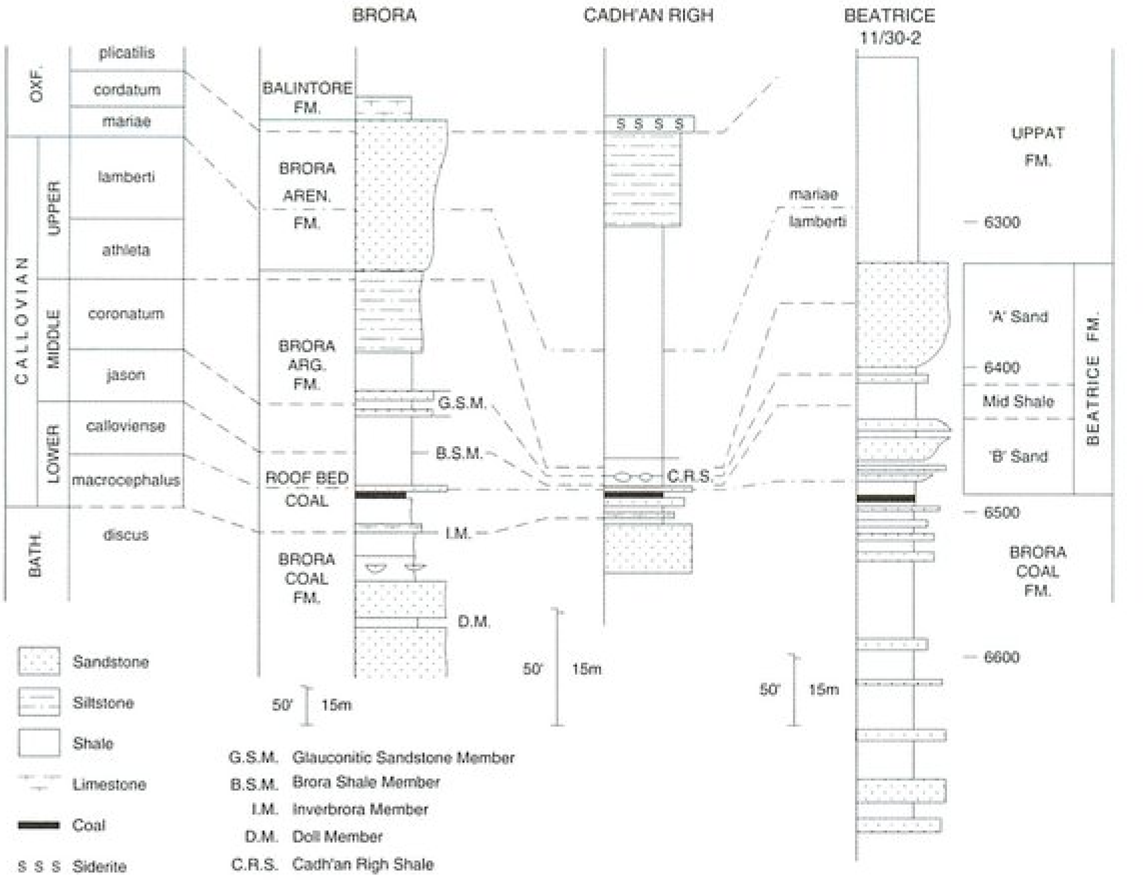
(Figure 9) Stratigraphy and lithofacies of the Triassic and Liassic rocks.



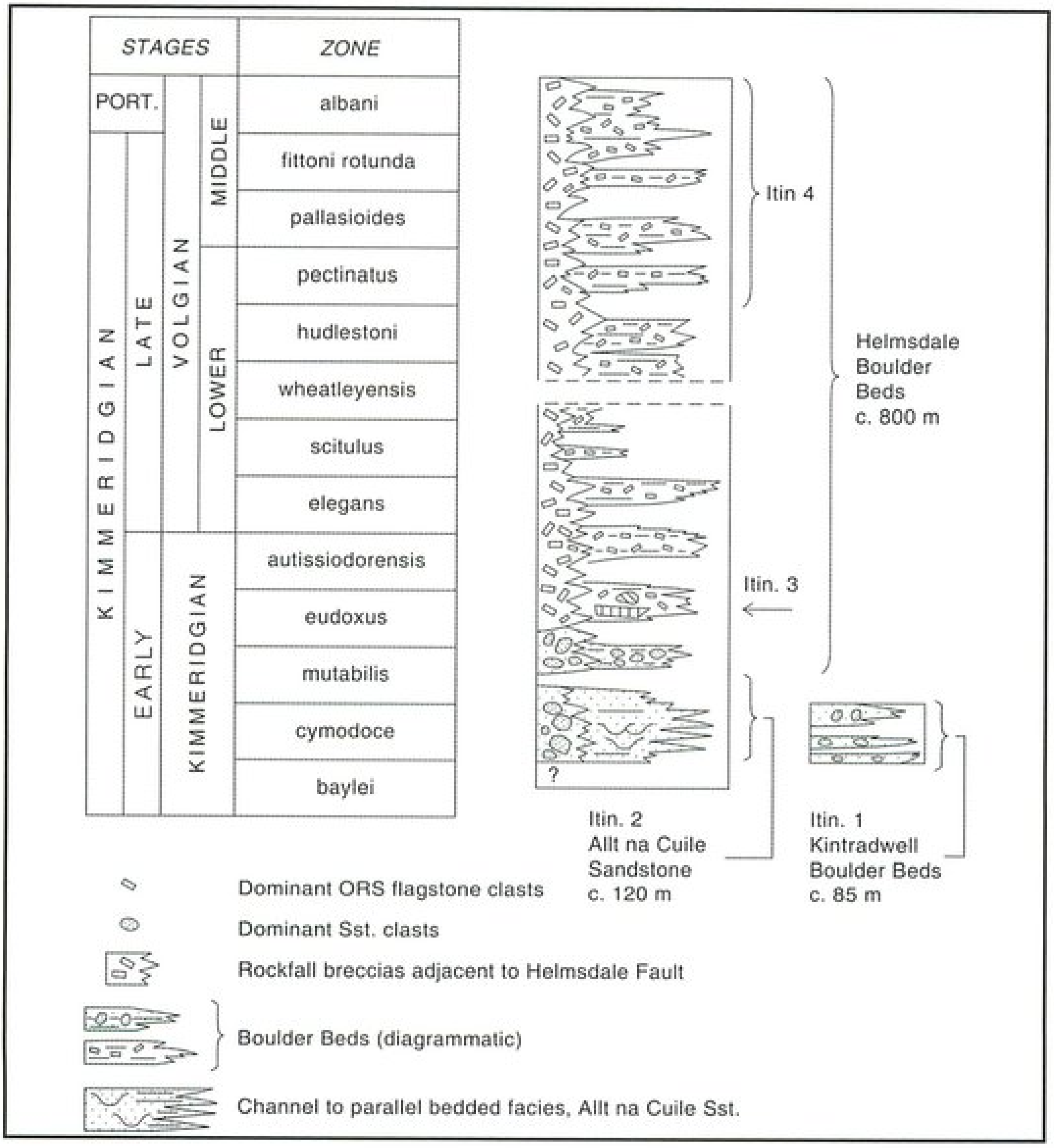
(Figure 10) Stratigraphy and lithofacies of the Bathonian and Oxfordian rocks.



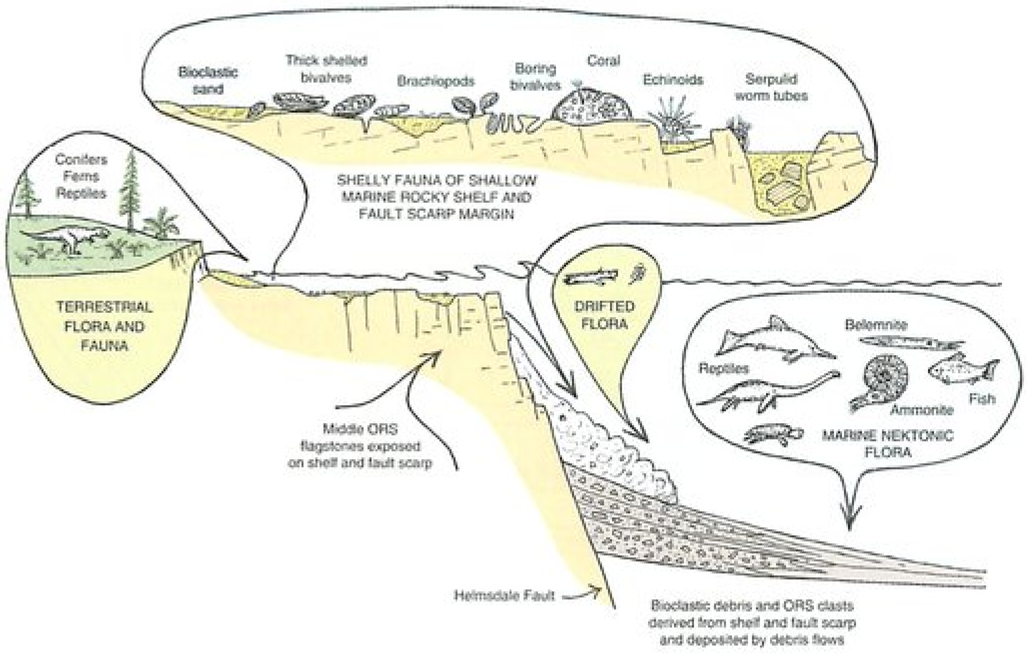
(Figure 11) Generalised palaeogeography of the Inner Moray Firth during the early Caliovian, showing the probable extent of the lagoonal area (After MacLennan and Trewin 1989).



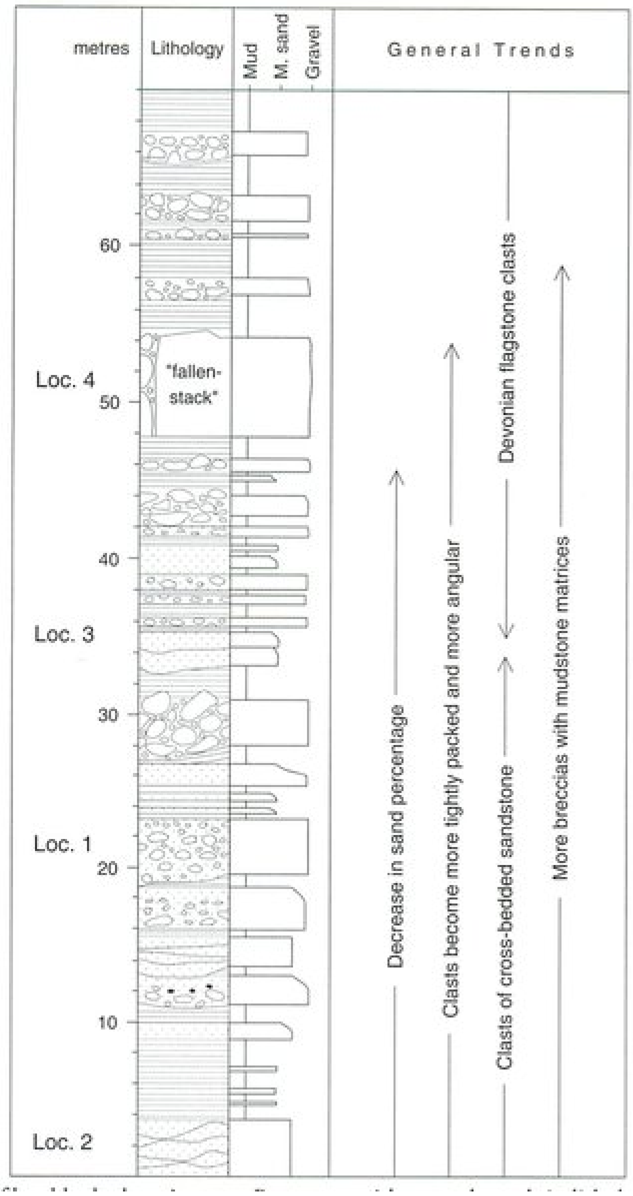
(Figure 12) Stratigraphic sections, nomenclature and correlations for the Callovian at three Inner Moray Firth Basin localities. Note variation in scales (Modified from MacLennan and Trewin 1989).



(Figure 3.2) Basic stratigraphy of the Kimmeridgian section with approximate stratigraphic positions of localities described in the excursion.



(Figure 3.3) Cartoon showing origin of fauna and flora associated with the Helmsdale Boulder Beds.



(Figure 3.17) Log of boulder bed section near Portgower with general trends in lithology and clast types (adapted from MacDonald (1985)).